BULLETIN

OF

The Geological Society of America

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TECHNOLOGY DEPARTMENT

VOLUME 71

NUMBER 3

March 1960

PUBLISHED MONTHLY BY THE SOCIETY

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Bulletin
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VOLUME 71 March 1960 NUMBER 3

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Subscription $15.00 per year.

Printing Office: Mt. Royal & Guilford Aves., Baltimore 2, Md.

Communications for publications should be addressed to The Geological Society of America, Dr. Frederick Betz, Jr., Secretary, 419 West 117 Street, New York 27, N. Y.

Please give notice of change of address 4 weeks in advance. Claims for nonreceipt of the Bulletin of a given month must be sent to the Secretary of the Society before the end of the second succeeding month.

Second-class postage paid at Baltimore, Md.
Accepted for mailing at special rate of postage provided for in Section 1103 Act of October 3, 1917, authorized on July 8, 1918.

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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 71, PP. 235-240, 2 FIGS. MARCH 1960

CARIBBEAN RESEARCH PROJECT: PROGRESS REPORT

BY H. H. HESS

ABSTRACT

Progress is reported in mapping the Eastern Caribbean area; 24 Ph.D. theses have been completed or are under way. One major objective is to interpret the available geophysical data in light of the geologic history of the past 100 million years.

Mapping of a series of quadrangles from Caracas to Tinaco in Venezuela has provided a cross section through the Cordillera de la Costa and Serrania del Interior. Several episodes of mid-Cretaceous metamorphism, rather than a single episode, are now recognized.

The concept that island arcs represent an early stage of alpine-type mountain building is rejected. Alpine-type mountains are developed along the thin margin of continental crust, island arcs on an oceanic type of crust. The two represent different kinds of reaction to the same type of tectonic forces. Germano-type mountains develop similarly in areas of continental crust of normal thickness. All three types can be seen along a single tectonic axis from the Antillean islands (island arc) into the coastal ranges of Venezuela (alpine-type) and thence to the Venezuelan Andes (germano-type).

Laboratory measurements of seismic velocities in fresh peridotite (8.4 km/sec) through partially serpentinized peridotite to serpentinite (5.7 km/sec) indicate that the so-called basaltic crust of the oceans may be peridotite two-thirds serpentinized. If so, Mattson's basement rocks which are serpentinites may be altered mantle rocks exposed at the surface. On the other hand MacKenzie has shown that true intrusive peridotites emplaced at temperatures above a minimum of 800°C. exist.

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INTRODUCTION

Hess and Maxwell (1953) described the nature and objectives of the Caribbean Research Project. Field studies during the last 6 years have necessitated modifications of some previously held concepts and development of new concepts. Project papers dealing with the Caribbean area are listed at the end of this paper and are shown in Figure 1.

ACKNOWLEDGMENTS

The field work in Venezuela described in this Bulletin was supported by the Ministerio de Minas e Hidrocarburos, Dirección de Geología, and four oil companies, Shell, Socony Mobil, Mene Grande, and Creole. The mapping program in Puerto Rico was sponsored by the Economic Development Administration of the Commonwealth and partly supported by Higgins funds of Princeton University. The writer's personal research on the Caribbean was carried out under a contract between the Office of Naval Research and Princeton University (contract onr 1858(10)).

VENEZUELA

A series of maps crossing the mountain belt diagonally from Caracas to Tinaco provides a

fairly complete cross section through the range and has clarified the stratigraphy and structure of the metamorphic rocks (Fig. 2). Additional information is obtained from G. C. are overlain unconformably by unmetamorphosed Paleocene rocks. O. Renz and K. Short (Personal communication), mapping from Acarigua to San Carlos, the western

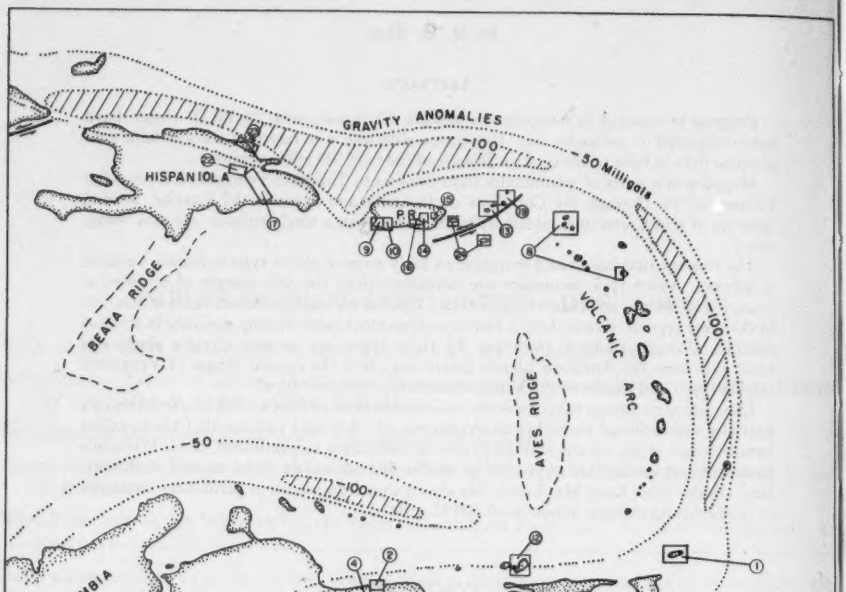


FIGURE 1.—EASTERN CARIBBEAN AREA THESES PUBLISHED AND IN PROGRESS AS OF 1959, DEPARTMENT OF GEOLOGY, PRINCETON UNIVERSITY

1. Maxwell
2. Dengo
3. Smith
4. MacLachlan
5. MacKenzie
6. Bushman
7. Shagam
8. Christman
9. Mattson
10. Slodowski
11. Konigsmark
12. Taylor
13. Donnelly
14. Otalora
15. Cadilla
16. Pessagno
17. Bowin
18. Oxburgh
19. Helsley
20. Menendez
21. Seiders
22. Palmer
23. Nagle
24. Whetten

Taylor's work on the island of Margarita far to the east and J. R. Bushman's work around Barquisimeto to the west. Perhaps the most serious misconception in our earlier work was to suppose that the metamorphism represented a single event in the history of the region. Some areas have undergone two or perhaps three such episodes, others only one. The areal extent of each of these episodes is different. Over most of the range the mid-Cretaceous (Albian ± metamorphism) was the most intense. Shagam has proven a second metamorphism in his area affecting early Maestrichtian rocks (the Paracotos formation), and MacLachlan has shown that these rocks

portion of the southern flank of the mountain range, found a fairly complete Cretaceous section with no mid-Cretaceous break, but all the rocks have undergone a low-grade metamorphism. Bushman finds a similar situation around Barquisimeto, and von der Osten and Zozaya (1957), who mapped an area to the south and west, believe that rocks as young as Eocene may be included in this metamorphism. Hundreds of miles to the east, K. Barr (Personal communication) found evidence of mid-Cretaceous metamorphism at the eastern end of the Northern Range of Trinidad.

Our original correlations between the meta-

morphic stratigraphy and unmetamorphosed section were based on an astute guess made by by Aguerrevere and Zuloaga (1937). The sequence Río Negro-Cogollo-La Luna is a facies sequence which in Venezuela transgresses time planes rather markedly. We now have accumulated almost enough fossil evidence and evidence supporting short-distance lithologic correlations to be able to date several levels within the metamorphic sequence. This will be dealt with in forthcoming reports by J. R. Bushman, T. A. Konigsmark, and others.

Island Arcs in Relation to Mountain Building

The idea that island arcs are an early stage in alpine-type mountain building probably is invalid. Instead island arcs and alpine mountain systems represent a case of parallel evolution. Island arcs develop in oceanic crust and alpine mountain systems develop in areas of thin continental crust along continent margins. Where the deformation penetrates deeper into the continent with normal crustal thickness, germano-type mountains result, comparable to the Northern Rockies in the United States or the Venezuelan Andes. The mechanics of deformation in these cases are similar, but the thickness and character of the crust are different, and hence the structural results are different. There also are differences in the igneous activity accompanying each of the three types.

Around the perimeter of the Eastern Caribbean, island-arc tectonics are well developed in the Greater Antilles. In the Lesser Antiles, island-arc tectonics are in a more youthful stage of development. In the coastal ranges of South America, alpine-type mountains have been formed which are in the same stage of development as the Greater Antilles. Our investigations suggest that the events in the last two areas mentioned are probably synchronous. The coastal ranges of Venezuela may be followed around to the southwest into the Venezuelan Andes which seem to be somewhat younger, but here, too, is typical germano-type mountain structure. This area is an excellent example of transitions in structure along a continuous belt of deformation from oceanic to marginal continental to continental crustal conditions.

Mattson has shown that serpentinized peridotites in Puerto Rico occur in the cores of major anticlines and are unconformable beneath late Cretaceous volcanic and sedimentary rocks. No granitic basement has been found in all the Great Antilles. In contrast to this the major anticlines of the Venezuelan Cordillera de la Costa commonly expose a basement of granitic gneiss. From this it was deduced that the Greater Antilles were formed in oceanic crust and the Venezuelan coastal mountains had a thin continental-type crust beneath them.

Mantle-Crust Relationships Below the Sea

North of the Puerto Rico trench and in the open ocean outside the Caribbean, the seismic velocity below the M discontinuity is 8 km/sec or a little higher. South of the Puerto Rico trench and under the Caribbean, it drops to about 7.4 km/sec (Officer *et al.*, 1957). The writer, assuming a peridotitic mantle, would attribute the lower velocity under the Caribbean to partial serpentinization of the mantle material (hydration).

A sample of completely serpentinized peridotite from Thetford, Quebec, was submitted to F. Birch at Harvard for laboratory measurement of seismic velocity. From his results a velocity of 5.7 km/sec is to be expected for completely serpentinized peridotite (density 2.60 g/cc) at shallow depth (2 kilobars). J. Green at the California Research Laboratory, La Habra, California, measured a completely fresh peridotite (density 3.34 g/cc). This is MacKenzie's peridotite, V336, from Tinaquillo, Venezuela. The seismic velocity was 8.4 km/sec. Green also measured a series of intermediate samples between serpentine and peridotite and found that the velocities varied linearly with density or per cent serpentinization.

From the figures given the top of the mantle under the Caribbean should be about 40 per cent serpentinized. One might ask whether the crust under the oceans which has seismic velocities generally between 6.4 and 6.9 km/sec might not also be peridotite two-thirds serpentinized rather than basalt. The dredging of serpentinized peridotite from fault scarps on the mid-Atlantic ridge (Shand, 1949) suggests this, as does the rather uniform thickness of this layer in all of the seismic profiles at sea. If this is true, confusion resulting from semantics must be avoided. The "crust" would in essence be altered mantle material.

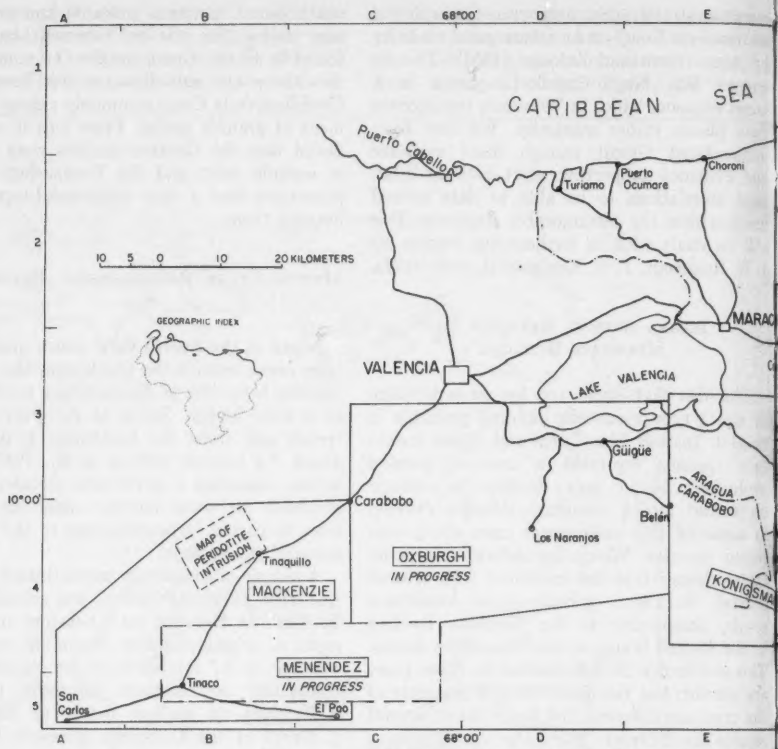


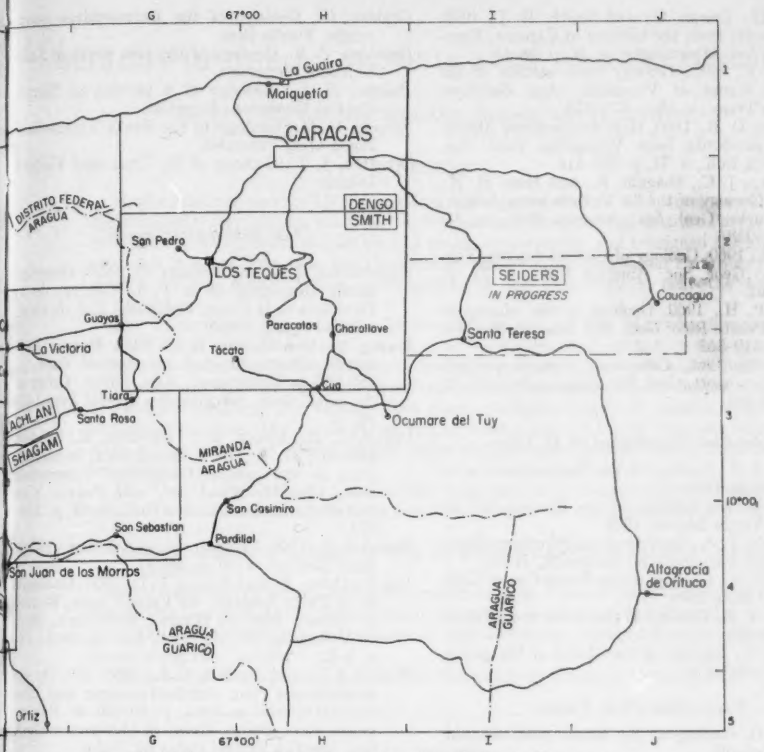
FIGURE 2.—INDEX MAP OF NORTH-CENTRAL VE[illegible]OWS ARE[illegible]

Considering Mattson's finding of serpentinized peridotite as the dominant rock forming the basement under Puerto Rico, one might reinterpret (Worzel and Shurbet, 1955; Ewing and Heezen, 1955; Officer *et al.*, 1957) seismic and gravity data for the section from the trench across Puerto Rico into the Caribbean. The seismic profile shows velocities from 5.5 to 6 km/sec and fails to show the M discontinuity under Puerto Rico. The thickness of the layer estimated from gravity data is 19 km for an assumed density of 2.67 g/cc or 25 to 26 km for density 2.84 g/cc (Worzel and Shurbet, 1955). The data could just as well be made to fit peridotite serpentinized to the proper degree to account for both the gravity data and seismic velocity as to indicate granitic or basaltic crust under Puerto Rico. Puerto Rico stands higher than the Caribbean floor because of a greater thickness of altered mantle material and a higher degree of serpentinization. The absence of a M discontinuity suggests that the transition here to unaltered mantle is gradational or the depth of alteration is too great to reach the bottom in the seismic profile.

INTRUSIVE PERIDOTITES

Inasmuch as the writer has been the stanchest supporter of peridotite magmas and is herein suggesting that the peridotites of Puerto Rico (and perhaps Oriente Province, Cuba) are altered mantle rocks exposed, where does this leave the peridotites of island arcs in general?

In Venezuela where the crust underlying metasedimentary rocks is granitic, sills and concordant lenses of serpentinized peridotite are fairly common (Dengo, 1953) and are best interpreted as igneous (fluid) intrusions. Shagam (1960) discusses serpentinized perido-



ows areas mapped or being mapped in the area from San Carlos to Caucagua

tites along the Santa Rosa and Agua Fria fault zones where solid emplacement is likely, but probably most of these have moved only a few hundred feet from sites of initial emplacement as fluids. Most significant, however, is MacKenzie's (1960) observation that a temperature of in access of 800°C. must have prevailed during the crystallization of the Tinaquillo peridotite after emplacement. The emplacement temperature could have been considerably higher. In any case solid intrusion is ruled out by the fact that the body would have had to have travelled upward scores of kilometers to have arrived near the surface at even 900°C. The writer concludes that peridotites representing mantle material in place and also intrusive peridotites emplaced as fluids initially but sometimes displaced short distances by solid flow are present in the eastern Caribbean region.

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Department of Geology, Princeton University, Princeton, New Jersey
Manuscript Received by the Secretary of the Society, July 8, 1958
Princeton Investigations of Caribbean Geology, No. 14

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 71, PP. 241-248, 2 FIGS., 1 PL. MARCH 1960

GEOLOGY OF THE LA VICTORIA AREA, ARAGUA, VENEZUELA

BY J. C. MACLACHLAN, REGINALD SHAGAM, AND H. H. HESS

ABSTRACT

MacLachlan mapped the La Victoria area in the period 1949 to 1951, accepting R. J. Smith's (1953) stratigraphic subdivisions. Shagam later demonstrated that the Paracotos formation of Smith contained within it a major unconformity and consigned the lower part of it to a new formation, the Tucutunemo, reserving the designation Paracotos formation for the upper portion characteristic of the type locality near the town of Paracotos.

The Tucutunemo formation lies conformably above the Las Mercedes formation of the Caracas group and hence is assigned as the uppermost formation in that group. Within this formation the Los Naranjos member, consisting in large part of flow breccias and tuffs, represents the beginning of volcanic activity accompanying the earliest stages of mountain building. The Villa de Cura group consisting largely of volcanic rocks is thought to lie above the Caracas group, but no contact between the two has been found. They are separated by a fault trough containing younger (Maestrichtian) Paracotos formation rocks.

The Tiara formation lavas postdate the main episode of metamorphism which has affected the Caracas and Villa de Cura groups but predate the Paracotos formation which contains Tiara pebbles.

Paleocene rocks lie unconformably upon the folded and slightly metamorphosed Paracotos formation.

Hornblende-quartz diorite and sodic granite intrude Caracas group rocks and are metamorphosed with them. Serpentinized peridotites occur along the Paracotos fault trough and are at least in part emplaced as solid intrusions. Gabbro intrusions also are found along this trough.

The structure is complicated in detail but comparatively simple in broad aspect.

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INTRODUCTION

MacLachlan mapped the La Victoria area in the period 1949 to 1951. This field work extended to the southwest the mapping of Dengo (1953) and Smith (1953). Shagam (1960) subsequently mapped southward from the La Victoria area to San Juan de los Morros (Hess, 1960, Fig. 2). His work showed a drastic revision of Smith's Paracotos formation was necessary. This required remapping of the central and southern portions of the La Victoria area. MacLachlan began this revision in

1955; it was continued by Shagam and J. R. Smith in the summer of 1956 and completed by Shagam in the fall and winter of 1956–1957. Hess spent several weeks with field parties in this area between 1949 and 1956 and has rewritten and condensed the field reports.

The purpose of this report is to fill in the pertinent information by which the gap between Dengo's and Smith's areas to the east and north can be closed with Shagam's to the south, and to recognize the priority of MacLachlan's work.

Plate 1 is a generalized geologic map of the area on the scale of 1/100,000. That part of the area discussed in detail is included on Shagam's Plate 1 (1960) at a scale of 1/50,000; it includes only the southern third of MacLachlan's original area.

Acknowledgments

The greater part of this study was sponsored by the Ministerio de Minas e Hidrocarburos of the Republic of Venezuela. In particular the work came under the Dirección de Geología, and special thanks are due to A. Schwarck Anglade, the Director, for support and encouragement. Also we wish to thank the many others in the Dirección de Geología who rendered every assistance possible.

Shagam and J. R. Smith in 1956 were supported by the Caribbean Research fund of the Department of Geology, Princeton University, to which liberal grants were made by four oil companies, Creole, Mene Grande, Socony of Venezuela, and Shell of Venezuela.

General work by Hess on correlation of Caribbean geophysical and geological data was supported by a contract between Princeton University and the Office of Naval Research (Contract N6 ONR-27008).

Thanks are due to H. H. Renz of Mene Grande Oil Company for identification of fossils.

Summary of Stratigraphic Relationships

Caracas Group

Dengo and Smith recognized the Sebastopol granite gneiss as basement rock below the Caracos group. This basement is not known to crop out in the La Victoria area. The Las Brisas formation and Las Mercedes formation of the Caracas group cover about one-third of the La Victoria area. The Las Brisas formation is typically a quartz-muscovite schist which not uncommonly is conglomeratic. The conglomerates as a rule have widely dispersed pebbles in a schist matrix (Smith, 1953, Pl. 2, fig. 1). The pebbles are granite, coarse albite-quartz rocks with a granitic texture, quartzite, and vein quartz. The formation is best exposed in the quebradas Cumbota (O17), Los Naranjos (N-15), Agua Blanca (O15), Valle Arriba (N9) and Río Pao (O14). For locations, *see* Shagam's Plate 1.

The Las Mercedes is typically a graphitic calcareous schist or phyllite with some thin-bedded and rare massive limestones. Near the top of the Las Mercedes, the Charallave conglomerate member forms a distinctive zone. The pebbles consist entirely of rounded quartz; the majority are translucent and the color of smoky quartz. This conglomerate is very coarse along the southern margin of the area, pebbles reaching a maximum of several inches in diameter, and it grades to a sandstone northward in the vicinity of Tejerias. For more detailed discussion of the Las Brisas and Las Mercedes formations, *see* Dengo (1953) and Smith (1953).

Above the Las Mercedes formation are rocks which Shagam (1960) has named and described as the Tucutunemo formation. The type section is in the hills south of the Río Tucutunemo not far east of Villa de Cura. The Tucutunemo formation appears to lie conformably on the Las Mercedes where it caps a hill 2 km north-northwest of Villa de Cura. It consists dominantly of dark phyllites but has intercalated limestones, feldspathic quartzose sandstones, and conglomerates. In the eastern part of the La Victoria area, the Los Naranjos volcanic member occurs near the base of the Tucutunemo formation and intertongued at higher stratigraphic horizons.

Los Naranjos Member of the Tucutunemo Formation

The volcanism represented by the Los Naranjos member was not fully appreciated until after the La Victoria area had been mapped. The member signifies the beginning of volcanism in the Caribbean Range. It appears stratigraphically not far above the Charallave conglomerate, which marked a change in sedimentation and probably indicates the first event in the tectonic cycle that later culminated in an Alpine-mountain-building episode.

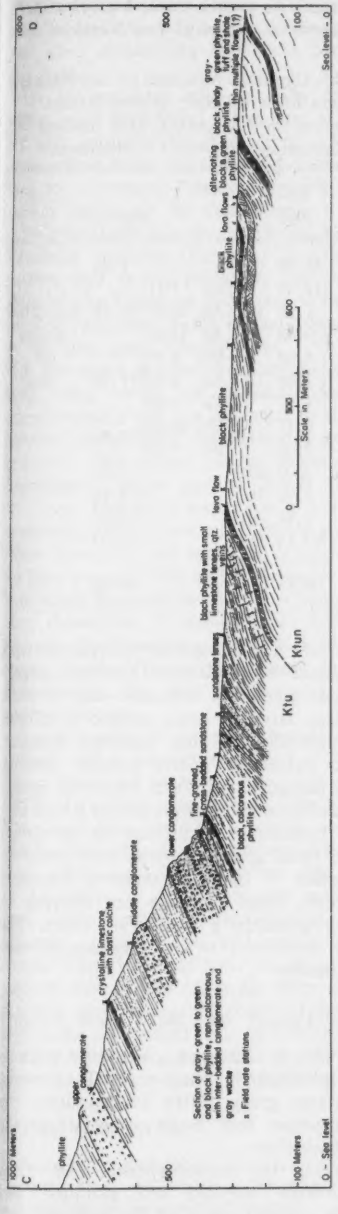

FIGURE 1.—CROSS SECTION SHOWING PART OF THE TUCUTUNEMO FORMATION AND THE LOS NARANJOS MEMBER IN THE VALLEY OF THE RÍO TORO
Section C-D, just below and to the right of center of Plate 1

The thickest and most complete section of the Los Naranjos member known is in the vicinity of the Río Pao. Here the member is 1200 m thick (Fig. 1). It thins abruptly westward so that in 15 or 20 km it is approximately 200 m thick. T. A. Konigsmark reports (Personal communication) that 20 km west of Villa de Cura it is absent in the section of the Tucutunemo formation which he has mapped. In the vicinity of the Río Pao, lavas are important parts of the Los Naranjos section, whereas the percentage of tuffs (now greenstones) increases westward. In the type section of the Tucutunemo formation, south of the river of that name and east of Villa de Cura, Shagam found greenstone metatuffs interfingered with the normal metasedimentary rocks of this formation.

Less is known of the Los Naranjos member to the east and northeast of the La Victoria area. The typical flow breccias of this member are well exposed in a quarry 8 km east of Tejerias. Rocks mapped by R. J. Smith north of Tacata (Hess, 1960, Fig. 2) as Tiara volcanic rocks also should be assigned to the Los Naranjos. This distribution indicates that the centers of eruption might have been some place between the Río Pao and Tejerias, but a more easterly source is also possible.

East of the Río Pao is a structure dipping generally southward. Here the Los Naranjos member lies upon dark phyllites of the Tucutunemo formation. The base of the latter formation is cut out by faulting, but it is thought that the bottom of the Los Naranjos member is not far above the base of the Tucutunemo. The volcanism apparently began abruptly with rapid extrusion of flows. No interfingering of volcanic rocks and sediments is found at the base. Toward the top of the Los Naranjos, dark phyllites of the Tucutunemo are intercalated with the volcanic rocks. This is best seen on the Cerro Palogacho (Shagam, 1960, Pl. 1, L, M13, M14). The phyllite increases in proportion upward. At the upper contact the volcanic rocks cease abruptly and are immediately overlain by thick calcareous feldspathic conglomerates with intercalations of dark phyllite. The passage from volcanic rocks and phyllite to conglomerate and phyllite is so abrupt as to give rise to a pronounced knickpoint on the Cerro Palogacho. Only in the headwaters of the Quebrada San Francisco (southwest end of Cerro Palogacho) (L13) were conglomerates found interbedded with the uppermost Los Naranjos rocks.

The Los Naranjos member appears in the stream bed of the Quebrada Los Naranjos (N15, N16) (type locality). It is also well-exposed on the quebradas Cambure and El Sapo (M12) and quebradas Cumbote and Volcan (N17). In the Quebrada Los Naranjos, water-polished outcrops show the fragmental character so common in these lavas. The lavas are flow breccias with angular fragments several inches across in a matrix of almost identical material. On wet surfaces the fragments and matrix differ slightly in color. The rock appears to have been shattered and a network of similar lava to have filled the fractures. In some cases the fragments were fractured before complete solidification and were drawn out into pear-shaped objects during flow. Thick flows may have brecciated tops and bottoms with massive lava in the middle. A particularly clear example of this was seen on the Quebrada El Sapo 1 km upstream from the junction with the Río Toro (M12). Pillow lavas were noted in two places on the Quebrada Cumbote (N17). The Los Naranjos flows are interbedded with finely laminated aphanitic rocks, probably metatuffs. The whole sequence of Los Naranjos rocks is thought to have been deposited under water, both because of the structural and textural features and because the rocks are included within the Tucutunemo formation, which not uncommonly has intercalated beds of fine-grained limestone.

Most of the Los Naranjos lavas are light green grading to darker bluish green in the more aphanitic rocks. A slight metamorphic foliation may be seen in some samples on fresh surfaces. In thin section the lavas are very uniform. They are characterized by a fine-grained felted texture made up of nearly colorless amphibole fibers or small plates with fibers growing from them parallel to the c direction. As in the hand specimens most are massive, and only an occasional one shows an indication of foliation. The rocks are sparsely porphyritic, with plagioclase, badly altered, as the most common phenocryst. Rare augites have been observed. These are perfectly fresh and show no signs of metamorphic recrystallization. Clots of epidote-clinozoisite and more rarely carbonate are present in most samples. Some appear to have been amygdule fillings and others veinlets or irregular bodies. The finer-grained samples have a turbid, almost opaque groundmass. Radiate aggregates of needles in these represent original plagioclase microlites. They are peppered with small specks of what appears to be leucoxene—no doubt an alteration product of original minute titanomagnetite grains. Table 1 gives a chemical analysis of a typical Los Naranjos lava.

TABLE 1.—CHEMICAL ANALYSES OF LOS NARANJOS LAVA FLOW AR 2037, SPILITIC BASALT
Analyst Doris Thaemlitz, Rock Analysis Laboratory, University of Minnesota

	AR 2037	Norm				
SiO_2	53.29	Q			1.86	
Al_2O_3	12.75	Pc	Or	1.11	52.27	An_{28} (Molecular per cent)
Fe_2O_3	1.19		Ab	36.15		
FeO	9.43		An	15.01		
MgO	5.93	Di	Wo	8.70	17.16	
CaO	7.68		En	4.50		
Na_2O	4.27		Fs	3.96		
K_2O	0.17	Hy	En	10.30	19.54	
H_2O+	2.03		Fs	9.24		
H_2O-	0.00	Mt			1.74	
TiO_2	2.03	Ip			3.80	
P_2O_5	0.41	Ap			1.01	
MnO	0.15	H_2O			2.03	
	99.33				99.41	

The rock is a fine-grained greenstone with little indication of foliation. It consists largely of fibrous pale-green actinolite and a sodic plagioclase. Irregular small patches of chlorite and clinozoisite and less common irregular granular patches of quartz possibly indicate original amygdules. A small veinlet of quartz with amphibole fibers growing into it was also noted. Leucoxene is present in moderate amount. Small specks of pyrite were noted by examination of the slide under a binocular microscope. Some of these are altering to limonite—probably a weathering effect. The rock is considered to be a metamorphosed spilitic basalt.

Rocks Younger than the Caracas Group

The Villa de Cura group, largely of volcanic origin, is thought by Shagam (1960) to overlie the Caracas group. After its deposition the metamorphism and major orogeny of the region took place.

Following the metamorphism, the Tiara basalts were intruded and extruded and probably covered much of the southern half of the range. Smith (1953) first described

these from the vicinity of the village of Tiara just east of the eastern border of Plate 1. Shagam found a thick section of Tiara on top of Villa de Cura rocks north of San Sebastían and some occurrences under the Morros of San Juan.

On the southern edge of Villa de Cura, pillow lavas were found at the base of a small hill with ruins of a chapel on top of it. Whether these pillow lavas are upfaulted Tiara or belong to a younger Paleocene episode of volcanism could not be determined.

Shagam (1960) has shown that the Paracotos formation contains abundant Tiara volcanic pebbles and is Maestrichtian. The relationships of the Paracotos formation to overlying rocks of Paleocene age are of particular interest in the area under consideration.

A few small patches of Paleocene sedimentary rocks overlie the Paracotos formation unconformably and are restricted to the same narrow belt in which the Paracotos formation is found. The largest area of these rocks is immediately south and southwest of Villa de Cura. The main rock type is a siltstone containing much volcanic detritus. A gray dense limestone bed which is being quarried for lime south of Villa de Cura appears to have been finely recrystallized during or immediately after deposition. It strongly resembles lithologically the limestones of the Morros of San Juan. Traces of algae and poorly preserved Foraminifera, the only fossils found in thin section, are rare.

Another patch of the same formation forms a small hill 4 km east-southeast of Villa de Cura. Near the center of the map area at 10°05′ N., a third area of these rocks is found. This area was mapped in some detail by MacLachlan (Fig. 1). On the west side of this area, a Paracotos gray limestone dips steeply to the north. It strikes into and presumably goes under rather gently dipping (20°±) volcanic conglomerates and volcanic sandstones. The Paracotos rocks reappear on the western side of the hill with steep dips. At the west end of the outcrop area of the Paleocene rocks a detached layer of limestone rests upon the Paracotos formation. In samples of these H. H. Renz found the following fossils:

MacLachlan sample 452

Nummulites (*Miscellanea*) sp. (scarce)
Actinosiphon barbadensis (Vaughan), forma *caudriae* M. de Cizancourt (scarce)
?*Discocyclina* sp. (scarce)
Globorotalia sp. (scarce)
Rotalidae (scarce)
Bolivina sp. (scarce)
Margulina sp. (scarce)
Bryozoa (scarce)
Algae (common)
Corals (scarce)
Echinoid spines (common)
Gastropods (scarce)
Mollusk remains (common)
Stratigraphic determination: Paleocene

An oyster bed was found higher in the same sequence at the locality shown in Figure 2.

No younger sedimentary rocks were found in the area except for the Quaternary alluvial deposits. These deposits were not studied in detail. Aside from alluvium along the banks of the larger streams, there are extensive terraces along the western margin of the map area which represent higher stands of Lake Valencia.

Intrusive Igneous Rocks

Hornblende-quartz diorite.—A large body of diorite traverses the center of Plate 1 from east to west. It forms a high ridge. It is flanked on either side by rocks of the Las Briasas formation, which it intrudes. In some localities it contains abundant inclusions of what appear to be Las Briasas schist fragments. Small satellitic intrusions of diorite in the adjacent Las Brisas formation are common. The diorite weathers readily, so that fresh samples either in stream beds or deep road cuts are unobtainable. The feldspar is generally altered to a turbid opaque material, although traces of plagioclase twinning can still be seen. The hornblendes are stout prisms making up nearly half of the rock in some cases and having decidedly the appearance of igneous rather than metamorphic amphiboles. Large quartz grains are abundant in many samples; in fact the quartz content in places is so high that it suggests contamination by quartzose wall rocks. Intrusive sheets of quartz-albite rocks, "soda granites," seem to be particularly abundant in the vicinity of the diorite. These intrude rocks as young as the Tucutunemo formation. They may possibly represent acid differentiates of the diorite. They seem to be highly susceptible to shearing; many are fine-grained quartz-albite-sericite mylonites. Except for the absence of ferromagnesian minerals the "soda granites" may be difficult to distinguish from some of the Las Brisas schists. The pres-

ence of sericite may indicate an original potassic feldspar destroyed during low-grade metamorphism.

Serpentinized peridotite.—The fresh unsheared serpentinized peridotite is best seen above the road cuts on Loma de Hierro on the eastern border of the map area. It is black and has rather uniformly scattered bastite pseudomorphous after enstatite. Serpentinization is complete in most samples. The texture outlines the original olivine crystals. The bulk of the serpentine is of the chrysotile variety; the ultramafic rocks near Caracas in Dengo's area are almost completely antigoritized. The Loma de Hierro serpentine appears to be a sheet-like body. It is cut by numerous small gabbro dikes which generally follow north-south sets of joint planes. They are much altered by the contaminating effect of the serpentine wall rocks.

Small slivers of serpentine are found all along the Santa Rosa fault zone from the west end of Loma de Hierro to Villa de Cura and also along the Agua Fria fault. At Loma de Hierro and just east of Villa de Cura the serpentine masses widen out to fill all or a large part of the area between the two fault zones. Except for one small lens of serpentine northwest of Loma de Hierro within the Tucutunemo formation, all the serpentines lie along the narrow belt between the faults, the same belt that is occupied by the Paracotos formation (of younger age). This is a puzzling structural relationship and the reasons for it are not at present apparent. The small lenses of serpentine on the faults might be ascribed to "solid intrusion" along these planes, for they are highly sheared. But this does not seem to be a reasonable explanation for the larger bodies, which in some cases spread across the whole area between the two fault zones and are not sheared, except locally. Shagam (1960) discusses the age of the serpentines.

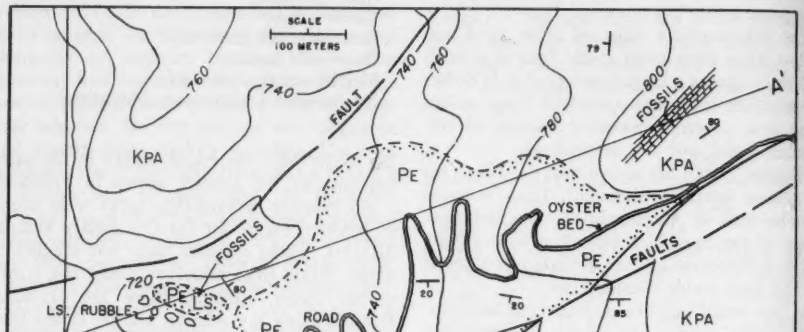

FIGURE 2.—MAP AND CROSS SECTION OF PALEOCENE ROCKS LYING UNCONFORMABLY UPON FOLDED PARACOTOS FORMATION SOUTH OF SANTA ROSA FAULT ZONE

Maestrichtian fossils were found in the Paracotos limestone outcrop in the northeastern portion of map, and Paleocene fossils in the small outlier in the southwestern portion. Location of oyster bed in Paleocene is also indicated.

Gabbro.—As with the diorite, the plagioclases of the gabbros are badly weathered. All that can be seen in thin section is a porcelaneous white opaque substance, although relicts of the twinning may be made out in some cases. The augite is commonly quite fresh. It is characterized by an extraordinarily perfect pinacoidal parting which gives it

the appearance of a mica. An optic axis emerges in these parting plates when the powders are examined under the microscope, so that it must represent either (100) or (001). In almost all cases the texture of the gabbro is subophitic, resembling that of the Tiara lavas but of much coarser texture. It is considered to be the intrusive facies of these lavas. In distribution it is limited, as are the serpentines, Paracotos formation, and Paleocene rocks, to the narrow belt between the Santa Rosa and Agua Fria faults.

Structure

Not much can be said of the structure that is not evident on the map and cross section. The area is divided into narrow N. 75° E. strips by large, steeply dipping faults. The most prominent feature is that forming the long straight valley from San Mateo to Tejerías, the La Victoria fault zone. It continues at least 40 km to the east across Smith's map, where it has been shown to be strike-slip with the north side moving east. It is a relatively young feature.

The Taguayguay fault may also be of strike-slip character. In the center of the area the Las Brisas formation and the diorite intrusion form a high block with downdropped Tucutunemo both to the north and south.

Many of the high-value dips shown on the map represent crumpled beds. If the average dips of formations as a whole are considered, especially south of the diorite, the structures are comparatively gentle. The metamorphism of the Caracas and Villa de Cura groups seems to have been produced to a great extent by rise of temperature rather than by intense dynamometamorphism, although shearing and the production of foliation play a part in the process.

The peculiar graben in which the Paracotos formation crops out has been mentioned previously. The mechanics of formation of such a structure remain obscure. That it may be the site of a fissure from which the Tiara lavas were erupted is suggested by the occurrence of the intrusive facies, gabbro, extrusive facies, and basalt along this valley and nowhere else in the La Victoria area. If this speculation were true, one might postulate collapse along the valley after the Tiara lavas were extruded and the remaining underlying magma crystallized. On the other hand the valley may be related to strike-slip faulting, and the basaltic magma may have merely found access to the surface along the fault planes.

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Manuscript Received by the Secretary of the Society, July 8, 1958

Princeton Investigations of Caribbean Geology, No. 11

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 71, PP. 249-302, 7 FIGS., 7 PLS. MARCH 1960

GEOLOGY OF CENTRAL ARAGUA, VENEZUELA

By Reginald Shagam

Abstract

The Central Aragua area is on the southern flank of the mountain ranges of north-central Venezuela. The south boundary of the map area separates the mountainous metamorphic zone from the low hills and plains underlain by unmetamorphosed rocks to the south.

Most of the area is underlain by a sequence of metamorphosed volcanic rocks more than 3000 m thick, the Villa de Cura group. This sequence has been subdivided into four conformable formations. The lowest three formations (El Caño, El Chino, and El Carmen) consist of metamorphosed spilitic basalts and associated volcanic sedimentary rocks. These rocks are now greenstones, some of which contain glaucophane. A striking feature of the metalavas is the presence of unaltered augite. The uppermost (Santa Isabel) formation is considerably more siliceous than the lowest three formations and consists of chlorite-quartz-albite schists and granulites; many rocks contain glaucophane. The Santa Isabel rocks closely approximate keratophyre lavas in chemical composition but are clearly of sedimentary origin. Dioritic rocks intruded into the Santa Isabel formation predate the main metamorphism.

North of the Villa de Cura group a sequence of carbonaceous phyllitic schists and metamorphosed lithic arenite sandstones and conglomerates and a distinctive limestone with large clastic calcite grains crop out. The sequence, the Tucutunemo formation, is considered to be the uppermost member of the Caracas group of metasedimentary rocks and to overlie conformably the Las Mercedes formation.

The volcanic rocks of the Villa de Cura group are considered to have been erupted after the deposition of the Tucutunemo formation. Possibly the volcanic rocks were erupted in a geographically separate area. Scanty paleontologic evidence suggests an Early Cretaceous age for the Caracas group.

In mid-Cretaceous times the main crustal deformation took place, accompanied by the intrusion of ultramafic rocks. The grade of metamorphism attained was not greater than that represented by the albite-epidote-amphibolite facies of regional metamorphism.

After the deformation another series of spilitic basalts and tuffs, the Tiara volcanic rocks, was extruded. These extrusions are texturally and mineralogically distinct from those of the Villa de Cura group. The Arrayanes formation on the southern boundary of the map area consists of lithic wacke siltstones, sandstones, and conglomerates composed largely of Tiara pebbles. The formation is dated by a Coniacian ammonite found near San Juan de los Morros. Neither the top nor the bottom of the formation have been observed.

In Maestrichtian to Paleocene times deposition of calcareous lithic wacke siltstones and sandstones and aphanitic foraminiferal limestones was continuous. The Maestrichtian sequence in the present mountain belt is referred to as the Paracotos formation. A second weaker orogeny began after the deposition of the Paracotos formation. The Tiara and Paracotos formations were caught within the deforming mountain belt and underwent mild dynamic metamorphism. The Arrayanes and Maestrichtian rocks to the south were merely carried northward on the south limb of this belt and were unaffected by the metamorphism. During Paleocene time, deposition was conformable with the Maestrichtian in the south but unconformable in the north. A third weak deformation took place in late- or post-Paleocene time.

The dominant structural trend of N.75°E. is explained by north–northwest—south–southeast compression. This compression could have resulted from an east–west shear couple produced by the movement of the Caribbean block eastward into the deforming arcuate tectogene. Normal faulting, possibly in response to isostatic adjustment, took place after the deformations. This faulting was accompanied by solid reinjection of the ultramafic rocks.

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INTRODUCTION

The Central Aragua region comprises approximately 650 square km, defined by the towns of Villa de Cura, San Juan de los Morros, and San Sebastián and the village of Tiara (Pl. 1). The southern boundary of the map area approximates the boundary between the metamorphic rocks of the mountainous Central Aragua area and the unmetamorphosed formations of the interior lowlands. The northern boundary roughly separates the metavolcanic rocks that underlie most of the map area from the metasedimentary rocks to the north.

The immediate aim of this study is to establish the relationship between the metasedimentary and metavolcanic rocks. In a broader sense this work attempts to contribute to the understanding of the processes and sequence of events that resulted in the formation of this alpine-type mountain belt.

The writer spent 21 months in the field, including July–September 1952; July–January 1953; July–January 1954; and July–October 1955. A considerable proportion of this time was spent in field work outside the map area.

Experience showed that outcrops in the streams are fresher and more continuous than those on the interfluves, with local exceptions. Hence, most traverses were selected accordingly. Most traverses are indicated on Plate 1 by the distribution of structure symbols. In most traverses measurements of structure and collections of specimen were made at 100–200-m intervals.

Laboratory studies were conducted in the Department of Geology, Princeton University, between the field seasons. Approximately 500 hand specimens and 300 thin sections were examined. In addition, the writer examined several hundred hand specimens and thin

sections of H. H. Hess, J. C. Maxwell, G. Dengo, R. J. Smith, J. C. MacLachlan, and D. B. MacKenzie.

Most petrographic descriptions in this report include an attempt to estimate the volume percentages of the constituent minerals. In certain instances mechanical grain-count analyses could be made. In most sections, however, especially in the fine-grained metamorphic rocks, such measurements were impractical, so that mineral proportions were gauged with the aid of visual percentage-estimate charts. Such figures should be treated with reserve.

Dengo (1953) has summarized early geological investigations in Venezuela. Recently, many studies have focused attention on the Caribbean area as a geological unit. This was stimulated by the location of oil in Venezuela and Trinidad. Hess (1932; 1938), on the basis of gravity measurements, applied the theory of crustal downbuckling; he later modified this (Hess and Maxwell, 1953). Woodring discussed the tectonics (1935) and paleogeology (1954) of the Caribbean region. Aguerrevere and Zuloaga (1937; 1938) accomplished the first regional study of the metamorphic rocks of northern Venezuela. Senn (1940) discussed the stratigraphy and structure of the Antillean region during early Tertiary times, and Sutton (1946) described the oil-bearing formations of the Maracaibo basin of western Venezuela. The available literature was compiled by Schuchert (1935), Liddle (1946) and Bucher (1952). Recent stratigraphic reviews are by Mencher *et al.* (1953) (on Venezuela) and by Kugler (1953) (on Trinidad).

Another phase of the work has been the detailed investigation of local lithology, stratigraphy, and structure. An enormous amount of work has been done in Venezuela by the petroleum companies; most of the results are unpublished. The researches of Hess and Aguerrevere and Zuloaga have been followed by a detailed study of the metamorphic rocks of the coastal ranges of Venezuela. This project includes studies by Dengo (1950; 1953) and Smith (1953) and unpublished Ph.D. theses done at Princeton University by J. C. MacLachlan (1952), D. B. MacKenzie (1953), J. R. Bushman (1958), the writer, G. C. Taylor (1959), and T. A. Konigsmark (1958).

Following local usage, the following terms have been retained; *morro* (castle—refers to any massive limestone that forms prominent cliffs and buttresses); *quebrada* (stream); *río* (river); *cerro* (mountain); *loma* (hill); *llanos* (plains); *serranía* (mountainous tract). The place name San Juan de los Morros is frequently abbreviated to San Juan.

The nomenclature of the sedimentary rocks used is that recommended by Williams, Turner, and Gilbert (1954). Petrographic terms for metamorphic rocks are used as follows:

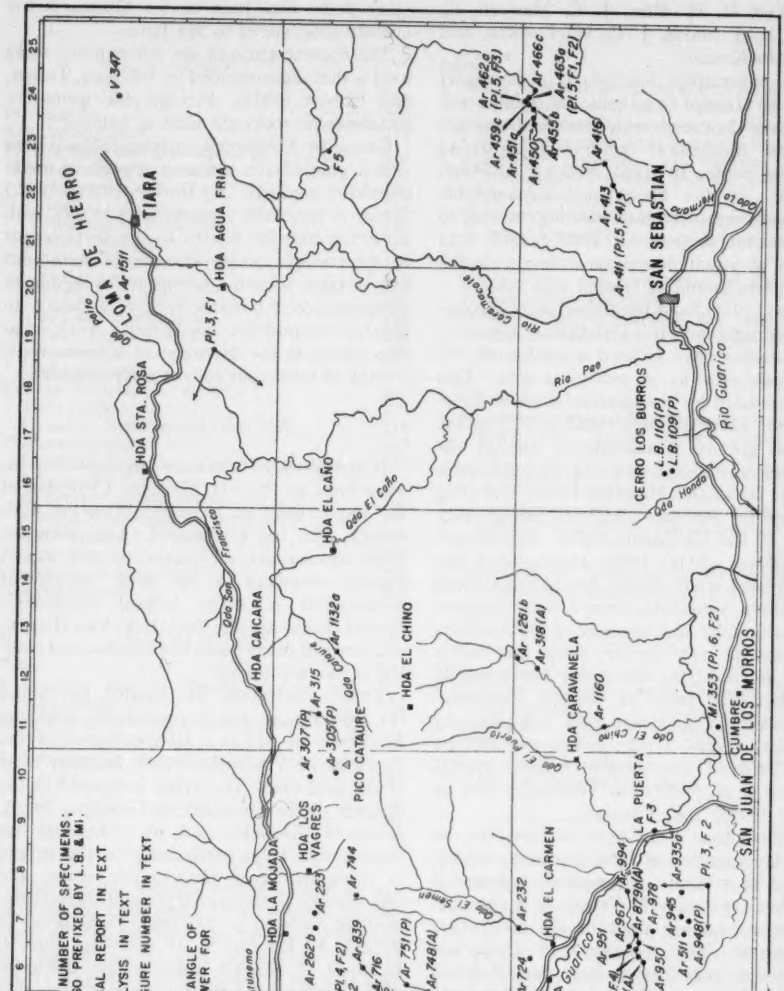
Granulite: A regionally metamorphosed rock with a granoblastic texture (no grade of metamorphism implied). (*See* Harker, 1939, p. 202.) *Schist:* A regionally metamorphosed rock with a marked foliation related to the development of macroscopic single crystals of micaceous and/or platy minerals. *Greenstone:* A regionally metamorphosed volcanic rock of andesitic to basaltic composition, displaying a weak foliation related to the development of microscopic crystals of micaceous and/or platy materials.

Acknowledgments

It is a pleasure to acknowledge my deep indebtedness to Prof. H. H. Hess, Chairman of the Department of Geology, Princeton University, who has maintained an inspiring interest throughout all stages of this study. Faculty members of the same department participated in many helpful discussions. Special thanks are due Prof. F. B. Van Houten, who devoted many hours to discussion and reading of the manuscript.

This investigation was carried out under the auspices of the Dirección de Geología, Ministerio de Minas e Hidrocarburos, of the Republic of Venezuela, which financed most of the field work. The writer is grateful to the director of the Dirección de Geología, Dr. A. Schwarck Anglade, and his colleagues for considerable help, particularly in the supply of transport, aerial photographs, maps, and instruments. In this regard grateful acknowledgment is made to L. Miranda, F. Galavís, G. Rivero, F. Rossón, S. de Civrieux, and R. LaForest. A. Sabater is largely responsible for the compilation of the topographic map that forms the base of Plate 1.

During July–October 1954, part of the field work was financed by the Caribbean Research Fund of Princeton University, to which contributions were made by the Creole, Mene Grande, Shell, and Socony Mobil oil companies of Venezuela. Discussions with P. Leuzinger and H. H. Renz of the Mene Grande Oil Company, G. R. Heyl, E. Foley, and G. Pierce of the Creole Petroleum Corporation, and E. Mencher of the Socony Mobil Oil Company were particularly beneficial. A. N. Dusenbury (Creole), H. H. Renz (Mene Grande), P. Bronnimann


Ar 1234 LOCATION AND NUMBER OF SPECIMENS; SPECIMENS ALSO PREFIXED BY L.B. & Mi.
Ar 948 (P) PALEONTOLOGICAL REPORT IN TEXT
Ar 879 (A) CHEMICAL ANALYSIS IN TEXT
Ar 827 (Pl.6, F1) PLATE AND FIGURE NUMBER IN TEXT
HDA HACIENDA
Pl.2, F1 LOCATION AND ANGLE OF VISION OF VIEWER FOR PANORAMAS
HDA AGUACATE
HDA LA MOJADA
HDA CAICARA
HDA LOS VAGRES
HDA EL CAÑO
HDA EL CHINO
HDA STA. ROSA
HDA AGUA FRIA
HDA TIERRA BLANCA
HDA EL CARMEN
HDA CARAVANELA
HDA EL CHACAO
HDA MACUATA
PICO CATAURE
CERRO LOS BURROS
SAN SEBASTIAN
SAN JUAN DE LOS MORROS
VILLA DE CURA
LA PUERTA
LOMA DE HIERRO
TIARA
Río Guárico
Río Pao
Río Cenizo
Río Tucutunemo
Río Guárico
Río Tiara
Río Guárico
Río Guárico
Río Guárico

(Cuban-Gulf), and H. M. Bolli (Trinidad Leaseholds) very kindly identified fossil material supplied by the writer.

The Higgins Fund of the Department of Geology, Princeton University, supported part of the field work and most of the laboratory studies. Handsome field assistance was received from L. O. Nicolaysen during July–September 1953; from A. O. Fuller during July–September 1954; and from G. C. Taylor in July 1955. Discussions with fellow graduate students, especially M. N. Bass and J. R. Smith, were also highly profitable.

Physiography and Geomorphology

The Central Aragua region comprises a single mountain range that enters the western boundary south of Villa de Cura and trends approximately eastward across the map area. This region forms part of the Serranía del Interior, a mountainous tract which extends as far north as the Maracay-Paracotos-Caucagua line (Hess, 1960, Fig. 2, 2E-H-J). North of this line is the Cordillera de la Costa, which comprises a range of mountains notably higher (as high as 2900 m) than the Serranía del Interior. The latter passes southward into the low hills and plains of the llanos of central Venezuela. The transition, marked by the valley of the Río Guarico in the area between San Juan de los Morros and San Sebastián, is one of the most prominent physiographic boundaries of Venezuela.

The area is extremely dissected. The maximum topographic relief, that between Pico Cataure, 1622 m (Pl. 1, I10), and the Río Guarico, exceeds 1200 m. The interfluve slopes are markedly concave upward in cross section and are characteristically steep. Crest lines are sharp, in some cases only a few meters across. Valleys are commonly V-shaped (Pl. 3, fig. 1). With local exceptions the land forms bear little or no relationship to the composition or structure of the underlying rocks. Among the exceptions are the morros of San Juan and San Sebastián. These are prominent buttresses on hill slopes and ridge crests composed of massive limestone. The occurrences near San Juan display vertical faces more than 150 m high (Pl. 3, fig. 2).

The drainage pattern forms a crude trellis; it is partly controlled by the metasedimentary bedding units that underlie a large part of the area. All drainage is related to the Río Guarico, which has its source in the mountains west of the map area. At La Puerta (Fig. 1, B9) it passes out of the metamorphic province into an area of unmetamorphosed rocks, and near San Sebastián, 25 km to the east, it turns southward and eventually enters the Río Orinoco. Some tributaries to the Río Guarico which have their source to the north are of antecedent origin. The Río Pao, for example, displays well-developed entrenched meanders (Pl. 1, J-K16). The Río Tucutunemo, which forms the northwest boundary of the map area, passes through a small gorge near its junction with the Río Guarico (Pl. 1, E5). Probably capture took place at this point by the Río Guarico and formerly the Río Tucutunemo and the drainage area around Villa de Cura flowed northwest into the Lake Valencia basin (Hess, 1960, Fig. 2, D-E3). Possibly lowering of the water level in the lake as evidenced by raised beaches is related to such piracy of drainage basins.

The uplift of the Serranía del Interior and Cordillera de la Costa is probably related to isostatic readjustment following the mid-Cretaceous crustal deformation. Unmetamorphosed Paleocene sedimentary rocks, as in the Cerro los Burros area (Fig. 1, B16), have been involved in the uplift of the mountain belt, indicating that this uplift is post-Paleocene. The difference in elevation of the two mountain blocks does not necessarily imply two ages of uplift. Isostatic uplift may have been greater in the central portion of the deformed belt. The uplift of the Miocene-Pliocene Cabo Blanco group and of coral reefs of recent age along the coast line suggests that uplift has continued to the present.

While there is a degree of accordance of summit levels in the Serranía del Interior, no definite regional erosion surfaces exist within the mountain belt. Certainly in the Central Aragua area at least, not a single peak retains any evidence of gravel deposits or flat surfaces. Evidently tectonic uplift has been considerably more influential than erosional processes in determining land forms.

Locally, erosional processes have gained the ascendancy and produced small definite surfaces marked by a gently dipping planar surface and/or the development of gravel deposits. In the vicinity of San Juan de los Morros, three different surfaces are clearly defined. Well-developed terraces have been preserved along the course of the Río Guarico upstream from La Puerta. Thick gravel deposits dipping gently northward are located in the valleys west of the morros of San Juan (Pl. 1, B5). The local surfaces cannot be correlated from valley to valley. They are clearly related to local base levels.

Figure 1.—Location Map of Central Aragua Area, Venezuela

The hill slopes of the mountain belt are remarkably steep. The slopes are formed of a thick weathered mantle with rare bedrock exposures and are sparsely covered by short grasses. These steep unsupported slopes possibly originate as follows: in the early stages of dissection the rate of uplift, rock type, and climate control the steepness. When the weathering has progressed so that the grassy cover is no longer sufficient to bind the hill slope, landslides result. The floor of the slide parallels the former slope. The scar develops a covering of vegetation and attains metastability. Meanwhile, adjoining areas undergo the same process. Thus the hill face retreats laterally, yet maintains its angle of slope. The slide detritus is carried away by the drainage, and the retreat of the hill slope produces an erosion surface related to the drainage in its vicinity. There is scarcely a hill face in the map area which does not bear the scars of mass movement of the weathered mantle. The dissection of the mountains, viewed from high peaks, suggests that a volume of rock approximately equivalent to the present volume of the mountains has been removed by post-Paleocene erosional processes. The erosional process is essentially one of pediplanation, the theory of which has recently been reviewed by King (1949; 1953).

The mountain ranges of northern Venezuela and of the Andes offer unique opportunities for geomorphologic study, an aspect as yet barely touched in Venezuelan investigations. These opportunities stem from three sources:

(1) The mountain systems are both comparatively youthful, yet of different ages. Possibly the early stages and the rate of land-form evolution may be determined.

(2) The evolution of the mountain systems has been marked at narrow time intervals by igneous and tectonic activity which provide fine date lines for determining the succession of geomorphic events.

(3) A variety of climates from alpine through tropical to desert are closely associated in space, so that their effect on land-form evolution may possibly be evaluated.

Such studies could have general application to fold-mountain systems throughout the world.

Older Metamorphic Complex

Caracas Group

General statement.—The older metamorphic complex includes the Caracas group, which is clearly metasedimentary, and the Villa de Cura group, which is dominantly a metavolcanic rock sequence. As only the uppermost (Tucutunemo) formation of the Caracas group crops out within the Central Aragua map area, it alone is described herein.

Tucutunemo formation.—East of Villa de Cura a spur of the main mountain range occupies an elongate structural basin of metasedimentary rocks assigned to the Tucutunemo formation. The formation is named for the Río Tucutunemo which lies near the northern boundary of the map in this area.

The Tucutunemo formation consists largely of blue sandy carbonaceous phyllites which range to feldspathic quartzose metasandstones and siltstones. Throughout the sequence are lesser volumes of calcareous quartzose grits and conglomerates. Near the top of the exposed sequence is a discontinuous but prominent zone consisting of a black fine-grained crystalline limestone associated with a calcareous quartz-pebble conglomerate. The limestone and conglomerate are diagnostic and in most instances may be readily distinguished from other limestones and conglomerates in the hand specimen. In the lower part of the formation there are a few thin beds of green aphanitic basic tuffs. The exposed succession is approximately 350 m thick.

Petrography

LIMESTONE (Pl. 4, figs. 1, 2):

Macroscopic characters: Dark gray black, submassive to foliated, fine-grained. Fresh surfaces display glinting cleavage surfaces of large calcite grains. This feature was noted in every outcrop and has not been reported from the limestone members of other formations. Quartz-calcite veins are locally abundant. Some weathered surfaces are light gray, others black. The normal pitted mode of weathering is common. Fossil remnants and large quartz and calcite grains commonly weather out on exposed surfaces. The beds form small cliffs on hill slopes and small buttresses on hill crests which are clearly visible from a distance. A member of the Amaryllidaceae, *Agave cocui*, commonly grows on outcrops and in their vicinity.

The trace of the outcrops is an oval with a major axis 8 km long. The limestone forms discontinuous lenses in a thick zone near the top of the exposed sequence and constitutes about 5 per cent of the total thickness of the formation. Two lenses are about 1.5 km long; most are less than 200 m long. No lens exceeds 15 m in greatest thickness, and most are about 7 m thick.

Bedding is everywhere present; beds are 3–30 cm thick. Clastic calcite locally displays apparent

poorly developed graded bedding. A moderate metamorphic foliation parallel to bedding was observed in most outcrops.

Microscopic characters: Calcite: clastic. As large rounded, ellipsoidal to spheroidal grains, which may be as much as 5 mm in diameter. They average about 0.5 mm in diameter. In some rocks they occur in two distinct size fractions. Lamellar twinning is common. Grain margins show replacement by groundmass calcite, controlled by the twin lamellae. Carbonaceous inclusions are common and are generally concentrated in the grain centers. Some inclusions form a regular pattern of dots, suggesting possible organic (algal?) remains (Pl. 4, fig. 2).

Some grains are surrounded by a weak halo of minute calcite rhombs and some angular embayed quartz grains. In a few specimens (Ar 716, 790, 828) only what are apparently relict outlines remain. Secondary growth of calcite at the terminations of the grains is not uncommon. The clastic calcite ranges from 5 to 20 per cent by volume of the rock.

Groundmass calcite: commonly as minute imperfect rhombs (average 0.03 mm in diameter); less commonly as minute granules or aphanitic aggregates. Groundmass calcite replaces the margins of the large clastic calcite and quartz grains. It is the dominant constituent of the rock, constituting 50–80 per cent by volume.

Quartz: angular highly embayed grains which average about 0.2 mm in diameter. The grains are better sorted in some specimens than in others. Replacement by groundmass calcite has produced deep sinuous embayments and isolated remnants. Most grains have numerous inherited bubble trains. Inclusions of zircon, tourmaline, and other unidentifiable anisotropic minerals are widespread (*e.g.*, Ar 709, 803, 771a). In some grains these are in spiral or circular arrangement (*e.g.*, Ar 790). The commonest inclusions are minute calcite granules which not uncommonly form a zone just inside the grain boundary suggesting growth of the quartz during metamorphism.

Composite grains are not uncommon. All display wavy extinction. The quartz grains are nowhere in mutual contact. Quartz ranges in amount from accessory to 30 per cent by volume, generally in the range 5 to 10 per cent.

Plagioclase: as embayed grains 0.04–0.3 mm in diameter. The plagioclase is mainly the sodic variety, although some grains are highly saussuritized, suggesting original more calcic varieties. The mineral generally occurs in accessory amounts; in one specimen (Ar 712) it constitites 5 per cent by volume.

Other minerals: Muscovite: as ubiquitous single flakes and wispy shreds up to 0.5 mm long. The flakes are possibly detrital; the habit of the shreds suggests metamorphic development *in situ*. Muscovite forms as much as 2 per cent by volume. Small sand- to grit-sized grains of crystallized chert with much carbonaceous material are rare. Graphitic material: common as streaks in the groundmass, rounded blebs in single calcite grains, and possibly as algal remains in large clastic calcite grains (*e.g.*, Ar 262b, 809). Limonitic material: common along foliation planes. Rare pyrite cubes were observed in some specimens.

Macrofossil remnants occur in many outcrops on weathered surfaces. A few possible Foraminifera were observed in thin section Ar 262b. None were identifiable.

Texture: The clastic calcite (5–20 per cent) and quartz grains (1–30 per cent) are distributed throughout a very fine-grained granoblastic matrix of imperfect calcite rhombs. In some specimens the distribution of the large calcite grains is patchy. Generally these grains are poorly sorted; in rare cases crude graded bedding was observed. A few specimens contain no clastic calcite grains (*e.g.*, Ar 805), but in every other property they closely resemble the normal rock. The groundmass is notably equigranular, although scattered patches of coarser grain size do occur.

All specimens have a marked metamorphic foliation, and some display minute drag folds emphasized by graphitic material and muscovite. All minerals are elongated in the plane of foliation, some more strongly than others. Increase in metamorphism results in progressively coarser groundmass, and the clastic calcite grains are destroyed or left only as faint relicts. In all cases the foliation planes diverge around the detrital calcite and quartz grains.

Name: Fine-grained quartzose crystalline limestone

CALCAREOUS SANDSTONES, GRITS, AND CONGLOMERATES:

Macroscopic characters: These are dark-gray to dark-blue-gray, submassive to foliated, bedded rocks. They occur throughout the succession as thin zones (1–10 m thick) of poor persistence. The rocks weather to a yellowish-gray friable mass. They are commonly associated with the limestones described heretofore and constitute about 40 per cent of the total volume of the formation. The quartz grains and pebbles are commonly white, but locally black varieties like those in the Charallave conglomerate (Smith, 1953, p. 50) were observed.

Bedding features are not well preserved. Graded bedding is not uncommon but is poorly developed. All the rocks have a weak to moderate metamorphic foliation parallel to bedding.

Microscopic characters of the sandstones: Quartz: as large, highly embayed, single and composite grains up to 2 mm in diameter; commonly 0.5 mm. Bubble trains and lines of inclusions are ubiquitous. In some specimens (*e.g.*, Ar 816, 839) these are uniformly oriented normal to the foliation planes, implying origin of the bubble trains *in situ*. Boehm lamellae were observed only in quartz-rich varieties where the grains are in mutual contact. The lamellae are generally oriented normal to the foliation. The quartz has been extensively replaced by calcite.

Minute quartz grains in the matrix have been recrystallized to small granoblastic patches. Inclusions of zircon indicate a granitic source for some of the quartz; the remainder probably is largely of vein origin. It constitutes 30–70 per cent by volume, commonly about 40 per cent.

Feldspar: as poorly sorted grains of the same size range and shape as the quartz (average diameter about 0.5 mm). As a result of replacement by calcite the grains are highly embayed. Sutured boundaries are common where the grains are in contact with other hard minerals. Sodic plagioclase is the most common variety, but saussuritized calcic grains are not uncommon. Some potassium feldspar may be present. Feldspar makes up 10–25 per cent by volume of the rock, usually 10 per cent.

Pebbles: Pebbles of a variety of rock types occur in all specimens but one. The largest pebbles observed are about 3 cm in diameter. The most common are pebbles of vein quartz. Rounded fragments composed of large equigranular quartz and plagioclase of granitic texture are common, too. Other less common varieties include crystalline carbonaceous chert and quartz-albite granulite (*e.g.*, Ar 709, 702, and 253). These two closely resemble the metacherts and quartz-albite granulites of the El Chino and Santa Isabel formations respectively. The pebbles have all been replaced to some extent by calcite, and mortar structure is common (*e.g.*, Ar 702), making it difficult to distinguish single grains from pebbles. The pebbles constitute 10–40 per cent by volume, commonly about 15 per cent.

Calcite: generally occurs as imperfect rhombs (average about 0.1 mm in diameter) and minute granules. Calcite replaces all other minerals and ranges from accessory amounts (Ar 702) to 60 per cent (Ar 712) but generally constitutes about 30 per cent by volume. In one specimen only, relict clastic calcite grains were observed (Ar 253).

Other minerals: minute crystalloblastic muscovite flakes commonly in swarms along foliation planes (1–3 per cent); graphitic specks in calcite and streaks along foliation planes, in accessory amounts. Zircon, epidote, and an unidentified isotropic mineral of high relief were observed in nearly every thin section. Pyrite cubes are uncommon.

Texture: The commonest rock type consists of poorly sorted quartz (35 per cent), feldspar (10 per cent), and rounded rock fragments (15 per cent), evenly distributed throughout a granoblastic matrix of calcite and minute quartz grains. The pebbles and grains are rarely in mutual contact.

A few specimens consist of well-sorted quartz (25 per cent) and plagioclase grains (10 per cent) evenly distributed throughout a granoblastic groundmass of calcite (60 per cent).

At the other extreme is Ar 839, which consists of sutured quartz (50 per cent) and plagioclase (15 per cent) grains and rock fragments (15 per cent) in a minute-grained granoblastic quartzose groundmass (15 per cent). Muscovite flakes constitute 5 per cent. Calcite is present only in accessory amounts.

The rocks have a weak to moderate metamorphic foliation emphasized by muscovite, graphite, and ore minerals. The quartz grains and some pebbles display a weak to moderate elongation in the plane of foliation. Metamorphic textures and structures (mortar structure, Boehm lamellae, etc.) and crystalloblastic minerals distinguish the rocks from the sandstones of the Paracotos formation.

Name: Feldspathic calcareous lithic arenite

METATUFFS:

Macroscopic characters: Medium-green, laminated to foliated rocks. They occur in beds 20–50 cm thick in sequences not exceeding 10 m thick. The metatuffs were observed in the lower portion of the formation in two traverses only, in the quebradas immediately south of the Hacienda Aguacate (Pl. 1, J5). The tuffs are interbedded with blue-gray carbonaceous phyllite and constitute a very minor proportion of the total thickness of the formation in this area. In hand specimen they are closely similar to the tuffs of the El Caño formation.

Microscopic characters: Highly embayed tattered laths of albite up to 0.1 mm long, elongate prismatic grains of clinozoisite and common epidote up to 0.4 mm long, minute chlorite crystalloblasts, and streaks of leucoxenized ore minerals all are distributed throughout a very fine-grained, strongly foliated, pseudo-isotropic matrix of unknown composition. Some clinozoisite and epidote grains are concentrated in small augen. Small flat pebbles of fine-grained mafic volcanic rocks are not uncommon. Calcite-clinozoisite-quartz-albite veins are well developed.

Name: Mafic metatuff

PHYLLITE:

Macroscopic characters: Blue-gray, strongly foliated, aphanitic to fine-grained rock. This is the dominant rock type of the formation, constituting about 50 per cent of the total thickness. Silty to sandy variations are very common, but such rocks retain the blue color and strong fissility. Rare graded bedding was the only primary structure observed. Metamorphic foliation is strong and locally the rocks may be defined as schistose. Microfold lineation parallel to the strike of the foliation is ubiquitous; the same parallel to the dip direction is strongly developed close to faults. Spectacular contorted folding on a scale of centimeters was observed in every traverse. The weathered rock commonly displays a dark-red surface stain and develops a schistlike appearance.

Microscopic characters: In thin section the phyllite is a very fine-grained granoblastic rock composed of quartz (? per cent), feldspar (? per cent), and white mica. The last occurs in streaks of large well-formed single flakes. Sandy and silty varieties approach the composition and texture of the sandstones

described heretofore but contain a markedly greater proportion of white mica and less calcite.

In hand specimen these rocks and those of the Paracotos formation superficially resemble each other. Careful observation, however, has revealed several macroscopic and microscopic characters diagnostic of each formation (Table 3).

DEPOSITIONAL ENVIRONMENT: The presence of chemical limestone and a notable proportion of coarse-grained rocks points to a shallow-water-shelf type of sedimentation. The cross-bedding, ripple marks, and related structures normally associated with such deposits are lacking, whereas graded bedding is common, even though poorly developed. These features may be explained by either of the two following depositional environments:

(1) A marine basin with moderately deep water close inshore. This could be related to a faulted coast line.

(2) An inadequate rate of sedimentation to keep pace with the subsidence of a shallow-water marine basin, such that the deposits were seldom affected by the sorting processes operative within the compass of wave base.

The writer favors the first alternative for reasons explained in the section on correlation. The presence of zircon in the quartz and of detritial feldspar suggests a granitic provenance in part.

The intimate relationship of conglomerate and limestone should be noted. This association is common also to both the Las Mercedes and Paracotos formations and suggests that similar conditions of sedimentation were repeated throughout the depositional history of the metasedimentary rocks of the Cordillera de la Costa.

METAMORPHISM: The regional metamorphism that affected these rocks was low grade, yet of higher grade than that which affected the Paracotos formation. The phyllites have an abundance of white mica which has developed in many instances as large single flakes. They are actually schistose phyllites, whereas the Paracotos equivalents are phyllitic shales. All the limestones are crystalline and clearly display characters of deformation such as the flattening of calcite rhombs parallel to foliation planes. The sandstones and conglomerates likewise reveal evidence of deformation in the presence of recrystallized quartz grains, Boehm lamellae, mortar structure and the possible development of large flakes of white mica. Microfold lineation parallel to the strike of the foliation planes is strongly developed throughout the phyllites.

The metamorphism was sufficiently severe to destroy organic remains, fragments of which are common in the limestones.

The degree of metamorphism has an important bearing in determining the stratigraphic succession of formations in the Central Aragua area.

AGE AND CORRELATION: The formation is in fault contact with the Paracotos sequence to the east and south and is elsewhere isolated from other formations by the Quaternary alluvium of the rivers flanking its base. Furthermore no identifiable fossils were found. Hence the stratigraphic position of the unit within the area mapped is indeterminate. However, for the reasons presented in the section on correlation, these rocks are considered to lie conformably on the Las Mercedes formation of mid-Cretaceous age and to be unconformably overlain by the Tiara volcanic sequence and the Paracotos formation.

The lower and middle portions of the rock sequence included by Smith (1953, p. 52–54) in the Paracotos formation are very similar to the rocks described heretofore. Probably they represent the easterly continuation, along the strike, of the Tucutunemo formation and should be reclassified accordingly.

Villa de Cura Group

General statement.—The Villa de Cura group was originally defined by Aguerrevere and Zuloaga (1937; 1938) to include rocks ranging from mid-Cretaceous to Paleocene (morro limestone of San Juan). As a result of Smith's work (1953), much of this sequence has been redefined, and accordingly the term has lost its significance. The writer proposes to redefine the Villa de Cura group to include a sequence of metavolcanic rocks and associated fine-grained metasedimentary rocks which constitute the major portion of the Central Aragua map area.

The group can be conveniently subdivided into four formations as follows (Fig. 2):

Santa Isabel: The youngest formation, consisting largely of interbedded chlorite schists and various quartz-albite granulites and schists of metasedimentary origin. There are lesser volumes of metamorphosed lavas and cherts.

El Carmen: A thick series of spilitic basalts with conspicuous green augite phenocrysts and related metatuffs.

El Chino: A sequence of layered, fine-grained

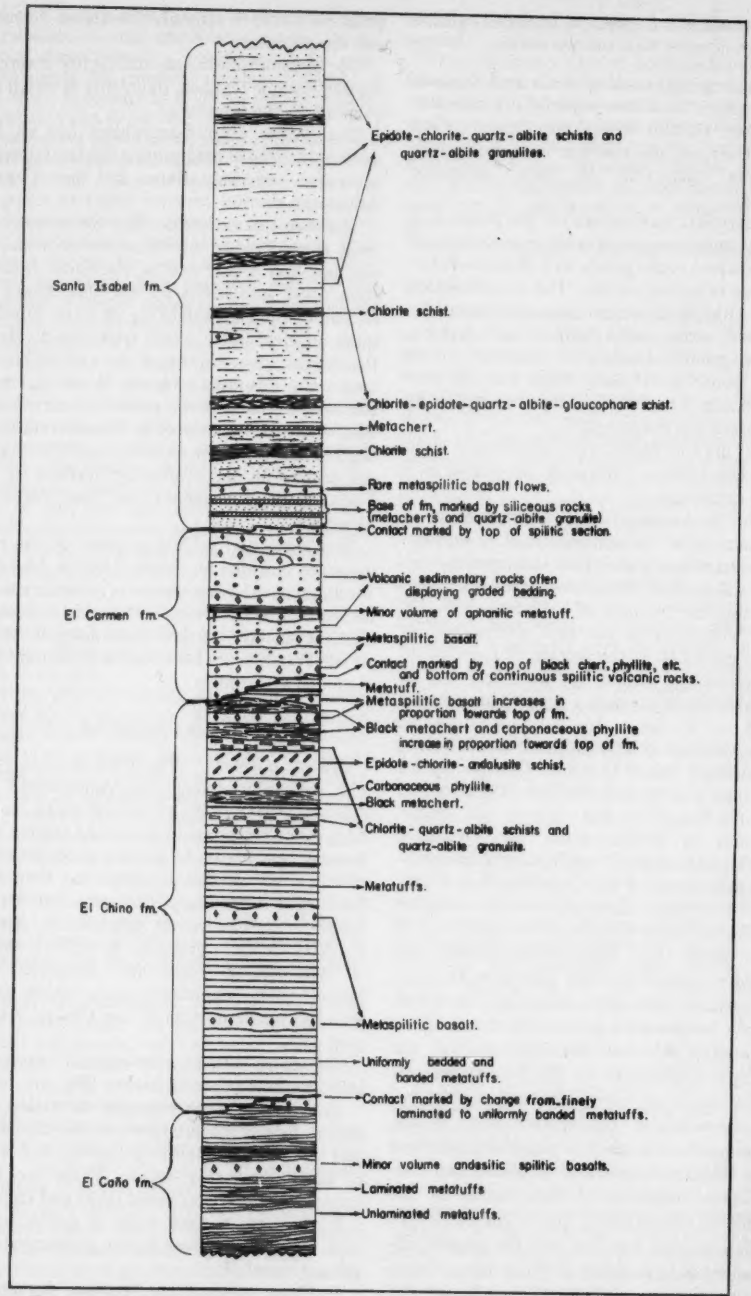

Santa Isabel fm.
El Carmen fm.
El Chino fm.
El Caño fm.
Epidote-chlorite-quartz-albite schists and quartz-albite granulites.
Chlorite schist.
Chlorite-epidote-quartz-albite-glaucophane schist.
Metachert.
Chlorite schist.
Rare metaspilitic basalt flows.
Base of fm. marked by siliceous rocks (metacherts and quartz-albite granulite)
Contact marked by top of spilitic section.
Volcanic sedimentary rocks often displaying graded bedding.
Minor volume of aphanitic metatuff.
Metaspilitic basalt.
Contact marked by top of black chert, phyllite, etc. and bottom of continuous spilitic volcanic rocks.
Metatuff.
Metaspilitic basalt increases in proportion towards top of fm.
Black metachert and carbonaceous phyllite increase in proportion towards top of fm.
Epidote-chlorite-andalusite schist.
Carbonaceous phyllite.
Black metachert.
Chlorite-quartz-albite schists and quartz-albite granulite.
Metatuffs.
Metaspilitic basalt.
Uniformly bedded and banded metatuffs.
Contact marked by change from finely laminated to uniformly banded metatuffs.
Minor volume andesitic spilitic basalts.
Laminated metatuffs
Unlaminated metatuffs.

FIGURE 2.—STRATIGRAPHIC AND LITHOLOGIC SUCCESSION IN THE VILLA DE CURA GROUP

metatuffs with lesser amounts of spilitic basalt, black metacherts, graphitic phyllite, and quartz-albite granulites and schists.

El Caño: The basal unit, consisting of a sequence of finely laminated aphanitic metatuffs with minor amounts of mafic and andesitic lavas.

The lowest three formations are unquestionably divisions of a single volcanic episode; the lithology appears to change markedly from the El Carmen formation to the schists of the Santa Isabel formation. However, the available information points to the consanguinity of the four formations. To sum up the relationships of the Santa Isabel formation to the underlying sequence the following points can be made:

(1) There is a narrow transition zone at the base of the Santa Isabel formation in which the El Carmen lavas are interbedded with typical quartz-albite schists. This is best seen in the Quebrada El Chino below the second ford (Pl. 1, D11) and in the Quebrada La Puerta above the first ford (Pl. 1, C9).

(2) El Carmen-type lavas are of minor volume but do occur throughout the Santa Isabel sequence as thin flows.

(3) The formations are structurally conformable.

(4) Quartz-albite granulites and schists very similar to those of the Santa Isabel sequence are intimately interbedded with the black cherts, lavas, phyllites, and tuffs of the El Chino formation. The implications are that the formations have attained the same general grade of metamorphism and that the provenance which gave rise to the Santa Isabel sedimentation was available in earlier times but was merely temporarily obscured by the volcanicity.

Hence the El Carmen-Santa Isabel boundary is here interpreted as reflecting only a minor discontinuity. There is no evidence to suggest a major unconformity.

Complex folding and faulting prevent accurate measurement of the exposed thickness of the group in Central Aragua. The minimum thickness is estimated at 3000 m, the maximum at 6000 m. The correct value is probably closer to the lower estimate.

The Villa de Cura group crops out along a narrow belt 180 km in length. D. B. MacKenzie (1953, unpub. Ph.D. thesis, Princeton Univ.) described Santa Isabel-type schists from the Tinaquillo area 100 km to the west (Hess, 1960, Fig. 2, B4), and R. La Forest (1952, unpub. report, Dirección de Geología, Ministerio de Minas e Hidrocarburos, Republic of Venezuela) observed these rocks in a traverse between Santa Teresa and Altagracia de Orituco 80 km to the east (Hess, 1960, Fig. 2, I3). The band averages about 15 km wide in outcrop. However in the Central Aragua region the northern boundary is a fault, and the southern boundary is formed by the overlap of younger rocks; hence the north-south distribution could be greater.

Southward the volcanic rocks disappear beneath a thick cover of unmetamorphosed sedimentary rocks. Rare basement outcrops north of Ortiz (30 km south of San Juan de los Morros) are either granitic or sandy phyllite to quartz-mica schist (P. Leuzinger, personal communication). Likewise outcrops in the El Baúl area 110 km south of Tinaquillo consist of metasedimentary rocks intruded by granites and felsic volcanic rocks according to Feo Codecido (1954). The metasedimentary rocks are quartzose sandstones, siltstones, and phyllites totally unlike the Villa de Cura assemblages. Hence the southern limit of the group is possibly not far beyond the present outcrop limits.

The persistence of the four constituent formations of the group as defined in the Central Aragua section is uncertain. Similar rock types in the same sequential arrangement were seen in the Santa Teresa-Altagracia de Orituco section. However, D. B. MacKenzie (1953, unpub. Ph.D. thesis, Princeton Univ.) described only Santa Isabel-type rocks and metacherts in the Tinaquillo area.

The rocks of the Villa de Cura group macroscopically appear similar, being more or less schistose green rocks. Slight variations in color and in the degree of schistosity can be directly correlated with mineralogic variation. Such characters are presented in the petrographic descriptions. The over-all similarity of the rocks is such that only in rare cases would the writer be able to assign a single hand specimen to its source formation with any certainty. However a suite of 5 to 10 randomly selected specimens would present no problem.

El Caño formation.—The basal unit of the Villa de Cura group takes its name from the Río El Caño (Pl. 1, J13–14), where exposures are particularly good. The formation is composed of finely laminated aphanitic mafic metatuffs, with minor amounts of mafic metalavas. The macroscopic and microscopic characters of the dominant rock types are described hereafter.

Petrography

Metatuffs:

Macroscopic characters: These are light- to dark-green, aphanitic, laminated rocks. They occur

throughout the formation and constitute about 70 per cent of the total thickness. Primary structures are plainly discernible. Bedding laminae are commonly 5 mm thick, alternately light and dark green. Within each lamina are second-order laminae 0.5 mm thick. The major laminae lens out abruptly and present the aspect of torrential bedding. Minute slump structures and scour-and-fill on a scale of millimeters and centimeters are ubiquitous. Intercalated with these finely laminated rocks are unlaminated varieties of considerably lesser volume, commonly in beds 20–50 cm thick.

Secondary structures are also well developed. These include brecciation, strike-slip and graben-and-horst faulting in the direction of dip, and drag folding. All these occur on scales from millimeters up to a few meters. Rarely a strong microfold lineation parallel to the strike of the beds is developed.

The metatuffs on the interfluves weather to a gray fine-grained rock of shaly appearance. In stream exposures the deposition of ferric oxide along lamination planes imparts a deep maroon color to some outcrops.

Microscopic characters: Albite: commonly as minute untwinned embayed laths 0.03 mm long; occasionally as larger embayed tabular porphyroblasts up to 2 mm long. Minute isotropic inclusions give a faint brownish color to the grains. Rarely albite occurs as interlocking embayed grains in lenses 3–6 mm long. Wavy extinction is common. The mineral constitutes 20–30 per cent by volume of the rock.

Augite: minute angular fragments 0.03 mm in diameter and large subhedral prisms up to 3 mm long. The mineral is commonly partly altered to epidote and chlorite. Large grains commonly display composite extinction. Augite generally forms 10 per cent by volume of the rock.

Common epidote and clinozoisite: as alteration products of augite and as discrete crystalloblasts (0.03 mm in diameter). Both constitute less than 10 per cent by volume of the rock.

Chlorite (penninite): as pale-green fibrous shreds and as minute crystalloblasts oriented along bedding planes. Chlorite constitutes about 30 per cent by volume.

Quartz: as minute embayed interlocking grains (0.03 mm in diameter) in cherty laminae and as larger grains with albite and calcite in veins. The mineral is of minor volume except in cherty laminae.

Calcite: as large idioblastic grains replacing all other minerals and as round granules that could represent replaced Foraminifera. The amount present rarely exceeds 5 per cent by volume.

Amphibole: minute rods and needles of a colorless to pale-green mineral, possibly actinolite, observed in all thin sections. They form about 5 per cent of the volume of the rock.

Other: Much of the rock is an aphanitic pseudo-isotropic mass of unidentifiable nature. This matrix is probably a chlorite-epidote-albite-actinolite intergrowth.

Texture: The white to pale-green laminae consist of minute angular embayed grains of albite in a pseudo-isotropic matrix of uncertain composition.

The dark-green laminae are composed of angular grains of albite and augite and minute perfect prisms of crystalloblastic epidote, clinozoisite, and pale-green amphibole in a pseudo-isotropic matrix. Large chlorite shreds and grains of carbonaceous material are concentrated along foliation planes.

The difference between the laminae is accented by a difference in grain size between adjacent laminae. The unlaminated variety of metatuff consists of minute angular grains of augite, epidote, and albite in a pseudo-isotropic groundmass rich in chlorite.

Shearing and stretching-out of grains parallel to the foliation planes is common in all specimens.

METALAVAS:

Macroscopic characters: These are deep blue-green, medium-grained, massive to coarsely foliated rocks. They occur as thin tabular bodies (1–5 m thick) fairly persistent and conformable with the bedding of the tuffs. The metalavas occur throughout the sequence but constitute 15 per cent or less of the total volume of the formation. Primary structural features were nowhere observed. Secondary structures are not uncommon and take the form of a coarse foliation parallel to bedding and a crude planar orientation of augite phenocrysts in the same direction.

Microscopic characters: The mineralogy is constant, but the relative proportions are highly variable.

Augite: as large stumpy prismatic phenocrysts up to 5 mm long and as anhedral granules in the matrix. Alteration to chlorite, green amphibole, and ores is commonly extensive.

Plagioclase: as tabular euhedral crystals which have been largely saussuritized. A thin outer rim of clear albite is common. This suggests an original calcic plagioclase. The mineral also occurs as subhedral grains in the matrix.

Amphibole: primary phenocrysts of an amphibole pleochroic in shades of moderate green, observed in one specimen only (Ar 1132a). The phenocrysts are up to 1 mm long and are commonly altered in part to chlorite.

Titaniferous magnetite: as primary phenocrysts in all specimens.

Quartz: rare anhedral grains, which probably constitute cavity fillings.

Texture: Type 1. Augite phenocrysts 0.5–3.0 mm diameter (40–60 per cent by volume) occur in a pseudo-isotropic fine-grained matrix probably composed mainly of chlorite.

Name: Porphyritic spilitic metabasalt.

Type 2. Large tabular phenocrysts of plagioclase up to 3 mm long (60 per cent by volume) and smaller stumpy augite phenocrysts up to 1.5 mm long (10 per cent by volume) occur in a matrix of minute plagioclase laths and augite granules. Primary microphenocrysts of titaniferous magnetite form up to 10 per cent by volume of the rock.

Name: Augite andesite

Type 3. Phenocrysts of prismatic hornblende commonly 0.5 mm long (45 per cent by volume) and large stumpy augite phenocrysts 1.5 mm long (10 per cent) are evenly distributed in a matrix consisting of subhedral plagioclase (30 per cent), augite granules (10 per cent), and magnetite microphenocrysts (5 per cent).

Name: Hornblende andesite (one specimen only)

METACHERT:

A minor portion (less than 5 per cent) of the El Caño formation consists of thin beds (up to 20 cm thick) of white to pale-green laminated metachert. The reader is referred to the descriptions of the metacherts of the Santa Isabel formation, which are similar, if not identical, to those in the El Caño formation.

METASANDSTONE?:

Macroscopic characters: White to pale-green massive-bedded (up to 1 m thick) rocks. This rock type constitutes less than 5 per cent of the total thickness of the formation. A coarse foliation parallel to the bedding is seen in places.

Microscopic characters: Quartz: as large angular and embayed grains. Bubble trains and rodlike inclusions of actinolite (?) are common.

Plagioclase: as completely saussuritized grains. Only relict tabular outlines were observed.

Others: fine crystalloblasts of chlorite (common); fresh albite, common in veins with quartz, calcite, and epidote.

Texture: The rock consists of an equigranular mosaic of interlocking quartz grains (30–40 per cent) and saussuritized plagioclase tablets (50 per cent). The quartz is strikingly angular. The origins of the rock and of its present texture are uncertain.

Name: Plagioclase-quartz granulite (?); metatonalite (?)

The total thickness of the El Caño formation is unknown, for the basal contact is a major fault. That portion exposed is not less than 300 m thick. The metatuffs constitute about 70 per cent of this. The validity of the appellation "tuff" is debatable. The mineralogical and chemical composition (Table 1, column 7) and the absence of diagnostic detrital minerals or sedimentary structures and textures suggest a pyroclastic origin.

Column 5 of Table 1 is the analysis of a typical lava of the El Carmen formation. The two analyses are similar except for the higher Al_2O_3 and lower MgO content of the tuffs. This could be related to weathering. The limited information permits only the general inference that the tuffs represent original basaltic material of the same family as that which gave rise to the El Carmen lavas.

The El Caño sequence is conformably overlain by the El Chino formation. Over a thin transition zone the finely laminated tuffs give way to the more coarsely layered tuffs of the El Chino formation.

El Chino formation.—Across the center of the map area is a broad zone of volcanic rocks named for the Hacienda El Chino (Pl. 1, G11). The contacts with the underlying El Caño metatuffs and the overlying El Carmen lavas are gradational. The minimum thickness is estimated at 1000 m.

The El Chino formation is composed largely of aphanitic to fine-grained, blue, green, and gray volcanic metasedimentary rocks. Primary bedding features have survived the low-grade metamorphism. The rocks are considered to be mainly water-laid tuffs. There is also a considerable volume of bluish-green porphyritic metabasalt identical in appearance and mineralogy to that of the El Carmen formation. Chlorite-quartz-albite schists very similar to those of the Santa Isabel formation make up a considerable volume also. A unique zone of epidote-andalusite-chlorite schist is located in the upper portion of the formation. Of minor amount, yet diagnostic of the El Chino sequence, are thin beds of laminated black carbonaceous metachert and graphitic phyllite. In three traverses a few thin lenses of coarsely crystalline gray marble were observed.

These rock types occur interbedded throughout the formation in sequences generally less than 20 m thick. The volume of tuff decreases, and lava, quartz-albite schist, chert, and phyllite increase upward in the succession.

Petrography

METATUFFS:

Macroscopic characters: In part these are gray-green to dark-yellow-green, aphanitic, subschistose rocks in beds 10–60 cm thick. In part they are medium-green, blue-green, and deep-blue aphanitic to fine-grained subschistose banded rocks. The bands are 1–12 cm thick. The metatuffs occur throughout the formation but particularly in the lower half, commonly in sequences 10–20 m thick. Individual beds are of moderate persistence, but in a stratigraphic zone the lithology is constant for long distances (km) along the strike. The rocks constitute approximately 50 per cent of the total thickness of the formation. Primary structural features such as scour-and-fill, graded bedding of silt-size grains, rare cross-bedding, and disturbed bedding (slump features) were observed in all traverses, usually on the scale of centimeters. Secondary structural characters include a moderate schistosity related to planar orientation of minute chlorite flakes parallel to bedding. Drag folding is

TABLE 1.—CHEMICAL ANALYSES OF ROCKS FROM THE VILLA DE CURA GROUP

Specimen number	1* Ar 879b†	2* Ar 978†	3*	4	5 Ar 318†	6 Ar 954†	7 Ar 748†
SiO_2	74.18	70.48	64	75.04	50.38	59.59	50.74
Al_2O_3	13.53	14.10	15	13.39	13.75	14.83	18.70
Fe_2O_3	1.28	0.93	1	1.61	1.38	4.09	1.24
FeO	1.04	2.64	4	0.37	8.15	5.02	6.43
MgO	0.92	1.95	4	0.18	8.79	2.78	4.86
CaO	0.61	0.69	3	0.40	8.94	4.19	6.30
Na_2O	7.34	6.74	7	6.36	3.61	5.55	4.50
K_2O	0.13	0.15	0	0.83	0.58	0.12	0.92
H_2O+	0.32	1.14	1	1.07	2.89	1.85	4.15
H_2O-	0.04	0.01	0	0.24	0.08	0.06	0.37
CO_2	0.01	0.02		0.10	0.03	0.05	0.38
TiO_2	0.34	0.49		0.10	0.64	0.98	0.83
P_2O_5	0.09	0.11		0.08	0.17	0.33	0.13
MnO	0.04	0.08		0.05	0.16	0.19	0.14
Total	99.87	99.53		99.82	99.55	99.63	99.69

* Analyses 1 to 3 represent a series ranging from ferromagnesian-poor quartz-albite granulite at one end to hypothetical epidote-chlorite-quartz-albite schist at the ferromagnesian-rich end

† Analyst: D. Thaemlitz, Rock Analysis Laboratory, University of Minnesota

Location of specimens

Column 1. Ar 879b; quartz-albite granulite with pale-brown amphibole rimmed by glaucophane (2 per cent). Quebrada Las Minas, 200 m east of the Hacienda Santa Isabel

Column 2. Ar 978; chlorite-quartz-albite schist. Tributary to the Quebrada Las Minas, 0.5 km south of the Hacienda Santa Isabel

Column 3. Suggested ferromagnesian-rich end member of the quartz-albite series obtained by rough extrapolation on the basis of thin-section observation

Column 4. Quartz keratophyre, Oregon. Analyst, J. G. Fairchild (Gilluly, 1935, p. 235, column 2)

Column 5. Ar 318; Porphyritic spilitic metabasalt, El Carmen formation. Seventh road ford in the Quebrada El Chino

Column 6. Ar 954; spilitic albite metadiorite. Quebrada Las Minas, 1 km west of the Hacienda Santa Isabel

Column 7. Ar 748; mafic metatuff, El Caño formation. Main quebrada east of the Macuaya serpentinite intrusive mass, about 6 km east of Villa de Cura

ubiquitous on a scale of centimeters and in places meters. Minute horst-and-graben faulting in the direction of dip is also common.

Microscopic characters: Albite: porphyroblasts. These are ragged anhedral laths and tablets and stretched-out augen-shaped grains. The ragged character is related to extreme replacement by chlorite. Not uncommonly only the relict outline of the porphyroblast remains. The grains are as much as 1.0 mm long but average about 0.1 mm long. Twinning is uncommon and follows the Carlsbad law when present. Unidentified inclusions of rods of anisotropic minerals are ubiquitous. Rarely black isotropic (carbonaceous ?) material rims the grains.

Crystalloblasts: minute (less than 0.03 mm in average diameter) subhedral untwinned grains in the groundmass which rarely can be distinguished from crystalloblastic quartz by a faint brownish turbidity.

Quartz: as minute straight-edged, subhedral grains in the groundmass. The grains average less than 0.03 mm in diameter. They contain numerous minute inclusions of anisotropic minerals.

Chlorite: occurs as large pale-green flakes concentrated in laminae, as small flakes replacing albite porphyroblasts, as an alteration product pseudomorphous after detrital hornblende, and as minute flakes throughout the groundmass. The larger flakes are birefringent (high first-order to low second-order colors). Small flakes are generally pseudo-isotropic. Chlorite is by far the commonest ferromagnesian mineral, constituting about 30 per cent by volume of the rock.

Actinolite (?): minute pale-green rods as inclusions in albite porphyroblasts and throughout the groundmass are too small for identification but are presumed to be actinolite.

Augite: fresh, angular, shattered grains up to 1.0 mm long. The mineral constitutes less than 5 per

cent by volume and in a few thin sections was absent.

Hornblende: angular grains of green hornblende of detrital origin, observed in most specimens. Pleochroism $\parallel Z$ = olive green, $\parallel X$ = pale green. Most grains are altered in part to chlorite. They make up less than 5 per cent by volume.

Other minerals: Pyrite: as cubes up to 5 mm on a side entirely enclosed by circular patches of radiating quartz which have replaced the sulfide in part. The sulfide is most common in the dark-blue variety of metatuff, exceeding 10 per cent by volume in some outcrops. Stilpnomelane: as wispy shreds along foliation planes and in quartz-albite veins. Minute specks of leucoxenized ore minerals: (very common). Carbonaceous material: as streaks along foliation planes.

Texture: Ragged albite porphyroblasts (5–20 per cent) show up as small clear patches in a minute grained pseudo-isotropic groundmass. The latter consists in part of small augen-shaped areas of granoblastic quartz-albite intergrowth. By far the greater part, however, is composed of a complex intergrowth of chlorite (30 per cent), actinolite (5–10 per cent), quartz (? per cent), albite (? per cent), and specks of opaque minerals.

Foliation planes parallel to bedding are strongly emphasized by chlorite flakes and granules of carbonaceous material. They commonly display strong microfolding. The foliation planes average 0.3 mm apart.

In some specimens minute chlorite flakes are oriented in two mutually perpendicular directions (throughout the thin section), each at 45° to the plane of foliation.

METABASALTS:

Conformably interbedded with the heretofore mentioned tuffs are lava flows of spilitic metabasalt. The rock is identical in hand specimen and thin section to the spilitic metabasalts of the overlying El Carmen formation, a detailed description of which appears in the next section. The metalavas constitute about 15 per cent of the total thickness of the El Chino formation. They occur in part in the lowest stratigraphic levels of the formation but most commonly in the upper half.

ANDALUSITE-EPIDOTE-CHLORITE SCHIST:

Macroscopic characters: This is a deep-yellowish-green, coarsely schistose, medium-grained rock of uniform appearance. The schist is almost entirely concentrated in a thick zone in the middle of the upper half of the formation. The rock was observed in all traverses at about the same stratigraphic level, but the thickness varies considerably. It constitutes about 5–10 per cent of the total thickness of the formation.

No primary structures were observed, except for a suggestion of original bedding planes at 2–5-m intervals. A strong coarse schistosity results from orientation of large chlorite flakes and is a characteristic feature.

Microscopic characters: Chlorite (penninite): occurs as pale-green fibrous shreds and flakes up to 1 cm long and as minute single crystalloblasts. Chlorite constitutes about 50 per cent by volume.

Common epidote: as anhedral granules (average diameter 0.05 mm) evenly distributed throughout the rock. The mineral forms 15–25 per cent by volume.

Andalusite: elongated colorless crystals averaging about 0.15 mm long, identified as andulusite by X-ray-powder spectrograph. The grains are non-pleochroic, and fine lamellar twinning parallel to (100) is common. $Nx = 1.664 \pm 0.002$. The mineral constitutes about 10–20 per cent by volume.

Quartz: as highly embayed interlocking grains with marked wavy extinction. Some untwinned albite may be included. Quartz forms 5–10 per cent by volume.

Texture: This is a strongly schistose rock with crude orientation of andalusite and epidote grains in the plane of foliation. Quartz occurs in small scattered lenticular patches.

Name: Andalusite-epidote-chlorite schist

CHLORITE-QUARTZ-ALBITE SCHISTS AND GRANULITES:

These are pale-grayish-green to medium-green, submassive to subschistose rocks. They occur in beds 20 cm to 1 m thick, commonly in sequences 5–10 m thick, interbedded with metalavas, cherts, and tuffs. These rocks are mainly concentrated in the uppermost quarter of the sequence. Both individual zones and the general stratigraphic zone of occurrence are of marked persistence. These rocks form about 15 per cent of the total thickness of the formation.

The rocks consist essentially of albite porphyroblasts in a fine-grained granoblastic matrix of quartz and albite. Chlorite and actinolite are concentrated along foliation planes. These schists and granulites are identical in appearance, mineralogy, and texture to those of the Santa Isabel formation.

METACHERTS:

Macroscopic characters: Grayish-black, laminated to submassive, aphanitic rocks. They occur in beds 5–15 cm thick. A chert sequence does not exceed 7 m and is commonly 50 cm to 2 m thick. The primary chert laminae, 0.5–1.0 cm thick, are commonly discernible. Impure varieties weather to a soft white schistose rock from which lamination planes protrude as minute blue-black ribs. Iron oxide stains on the surface are common. The metacherts are commonly visible from afar as small black cliffs on the hill slopes.

These rocks occur as thin zones, especially concentrated at the middle and uppermost levels of the formation. They constitute about 5 per cent of the total thickness of the formation. Primary bedding laminae are clearly seen. Secondary structures include drag folding and faulting referred to previously.

Microscopic characters: Quartz: subhedral grains with straight crystal edges (common). Two domi-

nant grain sizes were noted, about 0.05 mm and 0.01 mm in diameter. The latter are commonly rectangular in section and occur as inclusions in the larger grains. Other inclusions of minute anisotropic and opaque minerals are ubiquitous, but bubble trains are totally absent. Quartz constitutes about 80 per cent by volume, but in some specimens (*e.g.*, Ar 232) it is as low as 50 per cent.

Chlorite: As minute single crystalloblasts 0.03 mm in length. The mineral is common to every specimen but in variable proportions; up to 5 per cent by volume.

Albite: present in about 80 per cent of specimens. Prophyroblasts are well developed in some specimens but are rare or absent in most. Ar 1261b has grains up to 2 mm long (average about 0.8 mm). In Ar 232 all the albite grains are approximately the same size (about 0.15 mm long). The grains are partly idioblastic and in part highly embayed as a result of replacement by chlorite and amphibole. The mineral constitutes 10–30 per cent by volume of the rock.

Amphibole: Minute rods and needles and rare prismatic grains of pale-green amphibole (actinolite ?) are common but of minor volume (less than 5 per cent). Some grains display pleochroism in shades of pale brown (⫫ X) to pale green (∥ Z).

Opaque minerals: In every specimen examined minute black granules are concentrated along foliation planes and as inclusions in the quartz grains. They constitute 5–20 per cent by volume and are possibly responsible for the black color of the rock. Some are definitely iron oxides, but carbonaceous material probably predominates.

Accessories: common epidote, pyrite cubes, and an unidentified isotropic mineral, observed in one thin section.

Texture: The rock has a very fine-grained granoblastic texture with a faint foliation related to chlorite and amphibole flakes and rods. Generally albite porphyroblasts are few or absent. Sheared varieties have developed a very strong foliation, and the quartz crystalloblasts are markedly stretched out.

Name: Essentially albite-quartz granulite

CARBONACEOUS PHYLLITE:

Macroscopic characters: Three distinct varieties of carbonaceous phyllite were observed: (1) A gray, laminated, fine-grained rock with laminae 5–10 mm thick in beds 2–5 cm thick; (2) A deep-grayish-blue, foliated, aphanitic rock in beds 2–10 cm thick; (3) A black ultraschistose rock in beds up to 10 cm thick, interbedded with black laminated metacherts. These three varieties occur as thin sequences (not exceeding 15 m thick and commonly 1–5 m thick) throughout the formation. They are most prominent in the middle and uppermost levels of the formation and constitute 5–10 per cent of the total thickness.

The foliation or schistosity is related to the orientation of minute flakes of white mica and chlorite in the blue and gray varieties and graphite in the black varieties; in both cases it parallels bedding.

Only occasional grains of white mica, chlorite, quartz, and graphite were observed. A faint greenish sheen on foliation planes suggests more than accessory content of chlorite. The great bulk of the rock is too fine-grained for microscopic identification.

Name: Carbonaceous chloritic phyllite or schist; graphitic phyllite or schist

Whereas the metatuffs of the El Caño formation are finely laminated and indicate current bedding, the El Chino metatuffs are more coarsely layered, and the bedding indicates quiet depositional conditions. The lavas of the two formations are similar but not identical. In addition there are rock types restricted to one or the other formation only. Hence the two formations are readily distinguished in the field. However, the essentially volcanic character of the El Caño sequence is clearly maintained in the overlying El Chino formation.

El Carmen formation.—The El Chino-El Carmen contact is transitional. An arbitrary boundary was established at the uppermost black metachert zone. Above the chert is a succession of mafic metalavas and occasional dike rocks interbedded with metavolcanic sedimentary rocks. This map unit has been named for the Hacienda El Carmen (Pl. 1, E7).

The lavas are typically spilitic basalts with augite phenocrysts. They constitute about 30 per cent of the total thickness of the formation. The associated sedimentary rocks range from aphanitic to coarse-grained metatuffs. They were probably in part true water-laid tuffs and in part reworked volcanic sedimentary rocks. Primary sedimentary features such as graded bedding are ubiquitous and particularly well developed. Coarse-grained metatuffs closely resemble the metalavas, and only the bedding features and the shapes of the augite crystals distinguish them.

Primary structures in the metalavas (such as pillows) are rare, hence estimates of the thickness of individual flows were based on measurements of the interval between beds of metatuff. The thickest continuous lava sequence found was approximately 30 m thick (Quebrada La Puerta, north of the Hacienda Caravanela; Pl. 1, E10). Normal flows do not exceed 7 m in thickness. Likewise the thickness of a flow sequence is difficult to ascertain. Some hill slopes viewed from afar display a crude banding constituting units about 100 m thick.

It was not possible to observe the relative persistence of the individual lava flows or tuff beds. However, the presistence of the formation

as a whole is remarkable. It is known along a minimum strike length of 160 km. Within the map area the thickness of the sequence varies considerably, being greatest in the area between the quebradas Piritu and La Puerta (Pl. 1, D10–F10). The increase in numbers of dikelike bodies in this area suggests that it was near a volcanic center. The minimum thickness of the formation is estimated at 600 m.

Petrography

METALAVAS:

Macroscopic characters: Bluish-green, submassive to schistose rocks. A marked spotted appearance is related to the large olive-green augite phenocrysts, some of which exceed 1 cm in length. Vesicles are uncommon. The rock weathers to a pale-bluish clayey aggregate. The metalavas occur throughout the formation interbedded with metavolcanic sedimentary rocks. Individual flows are commonly 2–5 m thick. The lavas constitute about 30 per cent of the total thickness of the formation.

The only primary structural features observed are pillow structures. The best examples are in a road cut immediately east of the Hacienda Tierra Blanca (Pl. 1, E6). Metamorphic structures include a variable schistosity related to the flattening and planar orientation of augite phenocrysts and the development of chlorite. Rare outcrops may be massive; others are very strongly schistose. Uncommonly a crude lineation resulting from the orientation of augite phenocrysts parallel to the strike of the foliation was observed.

Microscopic characters: Augite: phenocrysts. These are large euhedral stumpy prismatic grains up to 1 cm in diameter, commonly 0.5–1.0 mm. Nearly all specimens contained more than one generation of phenocrysts, some of the largest displaying a thin zone at the periphery of the grain. Twinning parallel to (100) is very common. Commonly the phenocrysts occur in clusters of 3–20 grains; they constitute about 15 per cent by volume of the rock.

Groundmass augite occurs as minute euhedral to subhedral prisms and granules which average about 0.05 mm in diameter. These constitute about 15 per cent by volume of the rock.

Plagioclase: In most specimens the original plagioclase has been completely made over to metamorphic minerals. In some, relict elongate tablets up to 0.5 mm long were observed. These are all saussuritized, suggesting an original calcic variety. Relict plagioclase laths in the groundmass are also occasionally seen. The volume present is uncertain.

Magnetite: present in minute amounts. In one specimen only it made up about 5 per cent of the rock.

Chlorite (penninite): large pale-green, pseudoisotropic, fibrous shreds and small flakes. It is the most abundant mineral of the rock, constituting about 30 per cent by volume.

Amphibole: Minute rods and needles of a pale-green actinolitic amphibole are ubiquitous, constituting about 5–10 per cent by volume. In a few specimens accessory amounts of glaucophane as small needles were observed.

Albite: as highly embayed clouded tablets up to 1.0 mm long which have been largely replaced by chlorite and amphibole. The mineral probably exceeds 20 per cent by volume. In some cases the albite replaces augite phenocrysts.

Accessories: quartz and calcite which, with chlorite and albite, occur in veins and rare almond-shaped cavities. The latter could be filled-in vesicles.

Texture: Large augite phenocrysts (15 per cent) commonly in clusters of 3 to 20 grains and smaller relict plagioclase phenocrysts (5 per cent) occur in a fine-grained complex intergrowth of chlorite (30 per cent), and actinolite (10 per cent). Minute augite prisms (15 per cent) are evenly distributed throughout the groundmass. These minerals are in planar distribution and give rise to a moderate schistosity. Some of the albite appears to represent the replaced remnants of much larger grains. No semblance of ophitic relationships was observed anywhere.

Name: Porphyritic spilitic metabasalt

METATUFFS:

Macroscopic characters: Commonly light-yellowish-green, fine-grained, submassive to subschistose rocks. Variation to gritty rocks is not uncommon. Blue and green banded aphanitic tuffs are rare. These rocks occur throughout the formation interbedded with the metalavas. The aphanitic varieties are prominent only in the middle and uppermost levels. The metatuffs constitute about 70 per cent of the total thickness; the aphanitic beds constitute less than 5 per cent.

Primary bedding structures such as graded bedding and slump features are ubiquitous. The rocks have developed a weak to moderate schistosity resulting from the development and orientation of chlorite flakes parallel to bedding.

Microscopic characters: Primary minerals: Angular grains of augite and saussuritized plagioclase up to 2 mm long but commonly as minute fragments constitute a large proportion of the rock. Rare angular embayed grains of quartz of unknown origin were also observed.

Secondary minerals: Chlorite shreds and flakes, and rods of pale-green actinolite are major constituents. Albite porphyroblasts and crystalloblasts are not uncommon. Much of the rock is a fine-grained aggregate of unknown composition.

Texture: Angular grains of fresh augite and relict plagioclase occur in a fine-grained matrix in part composed of chlorite, amphibole, and albite. Primary bedding is emphasized by sharp discontinuities in grain size and by the variable amount of chlorite present in adjacent microlayers.

Name: Metamorphosed mafic tuff

The chemical analysis of a specimen of the lava from the Quebrada El Chino (Table 1, column 5) shows that it is a soda-rich basalt of spilitic character.

The spilite problem will not be discussed at length. In a controversial problem such as this it is inadvisable to use for examples rocks whose histories have been further complicated by regional metamorphism.

The preservation of unaltered augite in a metamorphic assemblage of chlorite, albite, and actinolite is remarkable. Such a general absence of alteration of augite is not reported elsewhere so far as the writer is aware. Typical are Park's (1946) comments on the spilites of Olympic Peninsula, Washington: "Most pyroxenes are highly altered though in a few sections pyroxene is surprisingly fresh." The apparent stability of augite was observed in specimens from every traverse and also in the El Carmen exposures on the Santa Teresa-Altagracia road 80 km to the east. Information bearing on this question was obtained from a study of the Tiara lavas which are described on a later page. These lavas are readily distinguished from the El Carmen volcanic rocks. They consist of augite and plagioclase phenocrysts in a groundmass of microlitic plagioclase subophitically related to augite. With rare exceptions, in the Tiara specimens examined, the groundmass pyroxene was altered to amphibole, epidote, and chlorite, whereas many of the augite phenocrysts are unaltered. The significance of this lies in the fact that the Tiara lavas were extruded after the main metamorphism. Hence the metastability of the El Carmen phenocrysts cannot be attributed to the metamorphism. Nor can it be attributed to the absence of hydrothermal activity in the El Carmen lavas, for the Tiara flows display evidence of strong deuteric hydrothermal activity; they are highly vesicular and veined.

The distinctive bluish green and pale blue of the fresh and weathered rock respectively and the tendency to form large rounded outcrops and boulders on the hill slopes are two of the rare surface indicators of the Villa de Cura group. These features, along with the constant texture and mineralogy and the remarkable persistence of the lavas combine to make the El Carmen formation a marker unit in the Villa de Cura group.

Santa Isabel formation.—The Santa Isabel formation comprises low-grade schists and granulites which occupy a broad east-west zone toward the southern boundary of the map area. The formation is named for the Hacienda Santa Isabel (Pl. 1, C7) where good exposures were found in several quebradas. These rocks constitute the uppermost formation of the Villa de Cura group, probably lying conformably above the El Carmen formation. In a narrow transition zone the lavas and tuffs of the latter formation are intercalated with the Santa Isabel-type schists.

The most common rocks are chlorite schists and quartz-albite rocks which display a continuous range from highly siliceous, ferromagnesian-poor granulites to less siliceous ferromagnesian-rich schists. The mineralogy is constant throughout this sequence; the proportions only are variable. Glaucophane, actinolite, chlorite, epidote, quartz, and albite occur as porphyroblasts in a fine-grained crystalloblastic matrix of quartz and albite. In addition to these schists there are minor volumes of metachert, mafic metalavas and pyroclastic rocks, and some metadiorite intrusions. The complete rock sequence is not exposed in the map area but that portion exposed has a minimum thickness of about 1000 m.

Petrography

QUARTZ-ALBITE ROCKS (Pl. 4, figs. 3, 4; Pl. 5, figs. 2, 3):

Macroscopic characters: These are laminated to coarsely schistose, fine- to medium-grained, layered rocks. The pure quartz-albite rock is pale green. With the appearance of chlorite, epidote, and green amphibole the color deepens gradually to a yellowish green. Presence of glaucophane produces a bluish-green color, the blue deepening as the amount of glaucophane increases. Likewise the schistosity of the rocks increases with the dark mineral content. It is hence possible from the estimation of color and schistosity of a specimen to arrive at a close approximation of its mineralogy.

Ferromagnesian-rich varieties weather to a soft brown foliated rock indistinguishable from a shale in appearance. Cherts and ferromagnesian-poor varieties form resistant ribs. Albite porphyroblasts commonly weather out on outcrop surfaces.

The quartz-albite rocks occur throughout the sequence as beds 20 cm to 1 m thick, interbedded with metacherts and chlorite schists. Individual beds are of strong persistence, but none are traceable across the map area. The most notable marker is a siliceous laminated rock poor in ferromagnesian minerals which forms a thin zone at or very close to the base of the formation. The quartz-albite rocks constitute about 70 per cent of the total thickness of the formation.

Primary sedimentary bedding is revealed by strong planar features at intervals of 20 to 100 cm.

cross which there are sharp differences of color, texture, and composition. Relict graded bedding and possible cross-bedding structures are rare. One especially good example occurs in the Quebrada El Chino 150 m below the second ford.

Moderate to strong metamorphic foliation parallels primary bedding. Rarely a weak microfold lineation parallels the strike of the foliation. Near large faults a strong dip lineation may be observed. Chevron folding parallel to strike is common near the Guarico Valley fault. Small horst-and-graben faults parallel to the direction of dip are common on a scale of centimeters.

Microscopic characters: Albite: porphyroblasts. Subidioblastic, embayed, tabular grains up to 5 mm long (average about 0.7 mm long). Two distinct size fractions are commonly present. Twinning is of moderate amount, commonly following the Carlsbad law when present, less commonly polysynthetic. Rarely the albite is untwinned. Commonly there is a faint brownish turbidity, except for a thin outer rim, related to the presence of clouds of minute inclusions. Flakes, rods, and needles of chlorite, pale-green amphibole, and glaucophane also occur as inclusions. Porphyroblasts are commonly sheathed by minute flakes of chlorite or by untwinned subhedral albite grains. Replacement along grain boundaries by chlorite and amphibole produces embayed porphyroblasts; extreme replacement produces the ragged anhedral albite of some specimens. Mild alteration to white mica is not uncommon; Nx = 1.530 ± 0.002. This suggests the composition An_{0-5}. Needles of possible clinozoisite were observed in the porphyroblasts of some specimens, suggesting original plagioclase of a more calcic composition. Albite porphyroblasts constitute 5–10 per cent by volume in ferromagnesian-poor rocks, 10–20 per cent in ferromagnesian-rich schists. Some of the schists are entirely devoid of porphyroblasts, although albite is a major constituent in the groundmass. In rare specimens albite occurs as subhedral lath-shaped microporphyroblasts (*e.g.*, Ar 951). In Ar 451a there is a transition from the small microporphyroblasts to the more common large tabular porphyroblasts.

Crystalloblasts: colorless, subhedral, untwinned, equidimensional grains averaging about 0.03 mm in diameter. These grains display the same faint brownish turbidity as the porphyroblasts.

Chlorite (penninite): as coarse pale-green fibrous shreds and as ubiquitous minute crystalloblastic flakes. Most commonly the mineral displays the normal pseudo-isotropic birefringence character. In some schists, however, chlorite is associated with epidote in large spherical glomeroblasts. In such occurrences it usually displays anomalous reddish-brown birefringence.

Chlorite ranges from accessory proportions in quartz-albite granulites to 20 per cent by volume in some ferromagnesian-rich schists.

Common epidote: ranges from minute granules 0.02 mm in diameter to large porphyroblasts 1.0 mm in diameter. The grains are commonly united in chains of 3 to 8 grains. In several specimens the epidote occurs as glomeroblasts of 3 to 30 grains (*e.g.*, Ar 1160, 463a, 459c). Generally these epidote clusters are markedly spherical (average about 1 mm in diameter), but some are tortuous blebs. The centers of these patches are commonly composed of calcite and large flakes of chlorite. Epidote occurs in accessory amounts to 20 per cent by volume, varying in sympathy with the other ferromagnesian minerals. Those schists which are glaucophane-rich have by far the largest proportions of epidote, and the grains are larger and more idioblastic.

Amphibole: Actinolite occurs as colorless to pale-green minute rods and elongate needles up to 0.2 mm long. In a few specimens (*e.g.*, Ar 455b) it occurs as idioblastic prismatic grains. Actinolite was observed in all thin sections, constituting as much as 10 per cent by volume, but generally less than 5 per cent.

Glaucophane forms fine needles (0.02–0.2 mm long) which occur either singly or in large fibrous aggregates. Rare elongate prisms up to 3 mm long were observed. In many of the glaucophane-rich rocks the amphibole needles have grown off chlorite flakes, and a transition from one mineral to the other is marked by a gradual change in pleochroism. Glaucophane occurs in all varieties of the quartz-albite rocks but is usually minor (2–6 per cent by volume). In some schists, however, it exceeds 30 per cent by volume.

The writer uses the term glaucophane to refer to a monoclinic amphibole which displays the following pleochroism: light greenish blue ∥ X; lilac lavender ∥ Z. The optical properties of the mineral are variable. Extinction Z ∧ C 5°–12°; dispersion V > r, strong.

In many specimens the variation in composition of both actinolite and glaucophane is indicated by the variation in the optical properties, particularly pleochroism. Actinolite ranges from its normal pale green to darker shades which are, however, distinct from those of a true hornblende. The glaucophane likewise varies to amphibole with either green or pale-yellowish-brown pleochroism. Thus in Ar 879b glaucophane rims an amphibole pleochroic in shades of pale yellowish brown. In Ar 466c the amphibole displays pleochroism in shades of blue green to pale green.

Quartz: porphyroblasts. Large xenoblastic embayed grains of quartz were observed in about 20 per cent of the specimens, but they constitute a minor volume of the rocks. These porphyroblasts include minute rods and flakes of actinolite (?) and chlorite, but bubble trains are rare.

Crystalloblasts: minute subhedral grains (average about 0.03 mm in diameter). These grains contain inclusions of very minute quartz grains of rectangular cross section in optical orientation contrary to that of the host quartz grain. Other unidentifiable anisotropic inclusions were also observed. The quartz grains are very similar in appearance to albite crystalloblasts, lacking only the faint turbidity.

Calcite: occurs as large crystals in veins and as irregular aggregates of minute grains replacing all other minerals. The amount present is highly variable, attaining 20 per cent by volume in some ferromagnesian-rich rocks. In some cases (*e.g.*, Ar 1701) it occurs as bands and streaks alternating with chlorite-rich layers.

Accessories: muscovite and stilpnomelane as wispy shreds. Pyrite cubes up to 5 mm on a side. Detrital augite (rare). Chalcopyrite and sphalerite were also observed in some specimens. Idioblastic crystals of sphene were noted in rare specimens, notably Ar 450.

Texture: Type 1 (Pl. 4, figs. 3, 4). Albite porphyroblasts occur in a very fine-grained granoblastic matrix of quartz and albite. A rough grain count performed by refractive-index measurements of 100 grains gave the ratio Ab:Q = 57:43 in the matrix. The albite porphyroblasts commonly occur in groups of 4 or 5 grains. In some cases they are clearly related to quartz veins, in other cases the veins cut the grains. Chlorite and amphibole as minute flakes and rods in planar orientation produce a weak foliation. Albite porphyroblasts may show weak alignment parallel to the foliation planes. Chlorite, actinolite, glaucophane, epidote = 5 per cent; albite = 60 per cent; quartz = 30–40 per cent.

Name: Essentially a quartz-albite granulite

Type 2. Type 1 grades into type 2. There is the same fine-grained granoblastic matrix of quartz and albite (Ar 967 gave Ab:Q = 68:32). Schistosity related to the planar orientation of chlorite and amphibole is very strong. The albite porphyroblasts display a weak to moderate orientation in the plane of foliation. Schistosity planes commonly diverge around porphyroblasts but not uncommonly terminate abruptly against them. "Van-and-lee" structure was observed to take the form of epidote and chlorite porphyroblasts forming a tail behind large albite grains. Albite and epidote porphyroblasts are concentrated in some laminae and absent from others. They commonly occur in two or more size fractions. Rarely the albite occurs in augenlike lenses. Glaucophane and actinolite constitute less than 10 per cent by volume; chlorite and epidote constitute 15–25 per cent; albite constitutes 50 per cent (volume of porphyroblasts to groundmass albite = 1:3); quartz constitutes 20 per cent. In a few specimens possible relict igneous textures were observed. In these schistosity is weakly developed, and the constituent minerals are notably xenoblastic.

Name: Essentially epidote-chlorite-quartz-albite schist (Pl. 5, figs. 1 and 2)

Type 3. Glaucophane is the dominant ferromagnesian mineral. It occurs as elongate needles and prismatic grains arranged in anastomosing fibrous aggregates. In small augen-shaped areas enclosed by the glaucophane the normal fine-grained matrix is composed of a mosaic of quartz and albite. Large porphyroblasts of common epidote and chlorite are associated with the amphibole laminae. In some specimens the epidote is crudely concentrated in some laminae apart from the glaucophane. This is best seen by the unaided eye on polished surfaces. In many instances albite porphyroblasts are absent in the glaucophane-rich schists.

Chlorite and actinolite constitute 10 per cent by volume or less; epidote constitutes 10–20 per cent; glaucophane constitutes 20–30 per cent; quartz and albite constitute 40–50 per cent (Pl. 5, fig. 3).

Name: Essentially epidote-quartz-albite-glaucophane schists. Rarely there is a separation into thin leucocratic and melanocratic laminae. These are glaucophane gneisses.

The glaucophane-rich schists constitute about 5–10 per cent of the total volume of quartz-albite rocks in the Santa Isabel formation.

CHLORITE SCHISTS:

Macroscopic characters: Ultraschistose plicated rocks of medium to deep green. They weather to a flaky brown aggregate similar in appearance to a shale. The chlorite schists occur throughout the sequence as zones 10–50 cm thick in sequences up to 30 m thick. Individual beds and zones are of poor persistence. They constitute about 20 per cent of the total thickness of the Santa Isabel formation.

No primary structural features were observed. The ultraschistosity is related to the development of large chlorite flakes parallel to the bedding of the adjacent metasedimentary rocks. A strong micro-fold lineation parallel to the strike of the foliation is common.

Microscopic characters: Penninitic chlorite occurs as large pale-green flakes as much as 1 cm long and exceeds 70 per cent by volume of the rock. The mineral commonly displays a radiate fanlike structure within each flake. Also present are small amounts of common epidote, pale-green amphibole, quartz, and albite. The rock has a very strong schistosity, and the foliation planes are commonly crenulate.

Name: Chlorite schist

METACHERTS:

Macroscopic characters: Laminated, pale-green, aphanitic rocks. Very rarely they are blue to black. The metacherts occur throughout the Santa Isabel formation interbedded with the quartz-albite rocks. These rocks display bedding laminae 0.3–0.5 mm thick in beds 5–30 cm thick in sequences not exceeding 3 m thick. They are of moderate to strong persistence and constitute 5 per cent or less of the total thickness of the formation. The thickest exposures occur south of the morros of San Juan (Pl. 1, A6).

The laminae are a primary bedding feature. Many quartz grains are stretched out, and orientation of minute chlorite flakes parallel to the foliation is common.

Microscopic characters: Quartz: minute, subhedral, straight-edged grains, about 0.03 mm in diameter. Very minute rectangular quartz grains

are enclosed within the larger grains. Inclusions of pale-green anisotropic and opaque minerals are common, but bubble trains are absent. The quartz grains of veins cutting the cherts are free of inclusions, but bubble trains are very common. In sheared specimens the grain size is larger and the grains have embayed margins; stretching-out of grains in the plane of the foliation is marked. Quartz generally makes up more than 80 per cent by volume of the rock but rarely is as low as 50 per cent.

Other: Albite forms small porphyroblasts and crystalloblasts, usually of minor volume. Rods and minute flakes of actinolite and chlorite and granules of epidote are ubiquitous but also of small volume. Minute rods of glaucophane are rare.

Texture: The rock has a very fine-grained granoblastic texture made up of interlocking quartz grains. A weak foliation related to the alignment of chlorite and actinolite flakes and rods was observed. East of the morros of San Juan (Pl. 1, B8) the primary chert lamination is well preserved, but the albite content is considerably higher than usual. Except for the lamination these rocks are very similar to some of the quartz-albite granulites described heretofore.

Name: Essentially a quartz granulite

METALAVAS AND TUFFS:

Such rocks were observed in most traverses as thin flows 1–5 m thick. The thickest and best exposed sequence is southeast of the morro of San Juan (Pl. 2A). Here more than 200 m of lavas and tuffs are interbedded with typical quartz-albite granulites and epidote-chlorite-quartz-albite schists. The lavas are bluish-green porphyritic basalts identical to the lavas of the El Carmen formation. Their intimate relationship with typical Santa Isabel schists precludes the possibility of their being infolded members of the former sequence. Dark-green augite phenocrysts up to 1 cm long give a marked spotted appearance to the rock. They constitute 10 per cent by volume of the rock. The remainder is an actinolite-chlorite-albite intergrowth. The reader is referred to the description of the El Carmen lavas.

METADIORITE:

Macroscopic characters: These rocks form thin (1–3-m) dark-green tabular bodies conformable with the bedding of the schists. The metadiorites crop out north and west of the morros of San Juan and less commonly in the lower reaches of the quebradas La Hermana (Pl. 1, E24, F25) and Honda (Pl. 1, B16). However, by far the largest volume occurs in the area east of the morros (Pl. 2A). Despite intensive mapping the exact mode of occurrence of the last-named is uncertain. Thin partings of quartz-albite granulite and schist within the mass suggest a series of sills or sheetlike bodies exceeding 200 m in total thickness. These sills are in general composed of medium-grained rocks, whereas the thin bodies north and west of the morros are all fine-grained.

Small crosscutting features are ubiquitous and point unequivocally to a primary igneous origin. The rocks are moderately to strongly schistose parallel to the bedding of the intruded schists.

Microscopic characters: Albite: as highly embayed tabular grains up to 1.5 mm long (average about 0.4 mm) in coarse-grained varieties. They have a faint brownish turbidity owing to minute opaque inclusions. Alteration to epidote is slight, suggesting an original sodic plagioclase. Replacement by chlorite flakes and actinolite and glaucophane needles is common, in some cases almost obliterating the albite grains.

Augite: identified in most specimens (*e.g.*, Ar 935a, 954) but commonly altered to epidote and chlorite. In coarse-grained varieties it occurs as elongate subhedral prisms up to 1.0 mm long, in finer-grained facies as small anhedral grains.

Metamorphic minerals: Epidote forms large grains pseudomorphous after augite and minute granules fringing and rarely enclosed by plagioclase tablets. Chlorite occurs as large porphyroblastic flakes and as an alteration product of augite. Actinolite and glaucophane as elongate prisms and needles are also major constituents. The latter commonly replaces plagioclase. Muscovite and stilpnomelane are present in accessory amounts along schistosity planes. Some specimens have quartz too, but whether it is primary or not is uncertain.

Texture: Original texture was observed in some specimens such as Ar 954. It is an intersertal texture of euhedral albite tablets (80 per cent) with anhedral interstitial augite (15 per cent). In coarse-grained varieties the augite forms elongate subhedral grains and is not interstitial. Subophitic relationships are rare. Titaniferous magnetite forms large single crystals (1–5 per cent).

Name: Soda-rich augite diorite (?)

In the metamorphosed rock the intersertal texture is preserved, but much of the plagioclase is replaced by a complex intergrowth of chlorite, actinolite, and glaucophane. Some albite porphyroblasts are developed, too. These minerals constitute up to 50 per cent of the rock by volume. Augite is converted to epidote, and ores form irregular blebs related to the alteration of the augite. A distinct schistosity is related to planar orientation of the metamorphic minerals.

PEBBLES:

Macroscopic characters: Scattered throughout the quartz-albite rocks of the Santa Isabel formation are large rounded boulders and pebbles. Many are pale yellow green and extremely hard, weathering out in outcrops. They are probably of intraformational origin. In many places the identical rock occurs as thin (5–30 cm) strongly boudinaged beds in close proximity. Extreme development of the boudins could be mistaken for boulders and pebbles in many instances.

In one locality north of the morros of San Juan (Pl. 2A, A5) there is a thin zone in which the pebbles are particularly abundant. Without a doubt these are of sedimentary origin, for they are of several varieties and bear no resemblance to the matrix, which is a coarsely schistose chlorite-quartz-albite schist. Where this zone is crossed by the San Juan-Villa de Cura highway there are excellent exposures in a road cut. The pebbles appear to be markedly stretched-out in the dip direction. West of the road cut in the lowest reaches of the quebrada Las Minas the pebbles and their orientation are far more clearly exposed. They are commonly platy with the largest diameter 3–20 cm. The pebbles display a crude alignment of the long axes in the dip direction of the matrix schist. This pebble zone is within the bottom quarter of the formation. The constituent pebbles make up about 5 per cent of the volume of the rock.

The pebbles in this zone are commonly white, very pale green, or pale yellow green. They are extremely tough and weather out readily.

Microscopic characters: The pebbles associated with boudinaged quartz-albite layers are quartz-albite granulite in composition and texture. The yellowish color is due to small amounts (1–3 per cent) of epidote.

Many of the pebbles from the zone north of the morros are clearly of volcanic origin, being markedly vesicular. They consist of an extremely fine-grained intergrowth of quartz and albite. The vesicles are filled in part at least with albite. Others are probably quartz-albite rocks, too, to judge from their leucocratic appearance in thin section, but are too fine-grained for positive identification of minerals. In some there are streaks of minute needles of pale-green amphibole and flakes of chlorite. Altered augite was observed rarely. Significantly the matrix rock (chlorite-quartz-albite schist) contains scattered fragments of fresh detrital augite (*e.g.*, Ar 994).

Name: Because of the uncertainty as to the detailed composition of most of these rocks, it is difficult to assign rigid petrographic names. The vesicular varieties are possibly derived from original keratophyric lavas.

In summary, the Santa Isabel formation consists largely of relatively pure chlorite schist (20 per cent) interlayered with quartz-albite rocks (70 per cent) which range from quartz-albite granulites poor in ferromagnesian minerals to glaucophane - epidote - chlorite-quartz-albite schists considerably richer in these minerals. These rocks are clearly a metasedimentary sequence.

GENESIS: Two chemical analyses of specimens of the quartz-albite series are shown in columns 1 and 2 of Table 1. The analyses are notable for the high Na_2O:K_2O ratios. Comparable analyses from the literature are rare, but a few—quartz keratophyres and soda rhyolites associated with spilitic lavas—are remarkably similar. One analysis listed by Gilluly (1935) is entered in column 4. The petrographic descriptions of Gilluly's rocks indicate clearly that these are primary flows, dikes, sills, and tuffs. Moreover, evidence clearly indicates extensive albitization of original andesine plagioclase. Such characters are completely lacking in the quartz-albite rocks of the Santa Isabel formation. The field evidence points conclusively to a metasedimentary origin. No keratophyre lavas or dikes were observed, except for pebbles of keratophyric lava in a thin zone north of the morros of San Juan. Of the plagioclase determinations made, none were more calcic than An_6, nor is there evidence of relict calcic plagioclase.

The writer believes that the chemical characters displayed by these rocks (high Na_2O:K_2O; low SiO_2:Na_2O; high Na_2O:CaO ratios) constitute a stable 'sink' in orogenic belts into which the products of magmatic, metamorphic, and sedimentary differentiation converge.

The low K_2O content is considered to be an inherited character derived from the original volcanic provenance. The high Na_2O content is attributed in part to the addition of sodium from the marine waters of the original basin of sedimentation. Silica too was possibly augmented by the same means. In this connection certain textural and mineralogic features are of interest:

(1) The metacherts throughout the Villa de Cura series contain minute crystalloblasts of albite and chlorite evenly distributed throughout the rock.

(2) The groundmass of the schists and granulites is commonly a very minute-grained interlocking mosaic of quartz and untwinned albite.

These features suggest a common origin for at least a portion of the SiO_2, Na_2O, and MgO content of the rocks, and further that these constituents were introduced by chemical precipitation at the site of deposition of the sediments. In a marine environment the occlusion of Na^+ and Mg^{++} ions by colloidal silica is well within the bounds of chemical possibility.

The texture of the rocks suggests an original fine-grained sediment, possibly a siliceous montmorillonitic shale.

No chemical analyses of the chlorite schists were made; however they consist almost entirely of penninitic chlorite with minor amounts of epidote, quartz, and albite. Analyses of pure chlorite schists (15 are listed by Phillips and

Hess (1936, p. 360)) show SiO_2 constitutes 25–35 per cent; Al_2O_3 constitutes 21–12 per cent; FeO plus MgO constitutes approximately 35 per cent; CaO, Na_2O, and K_2O are very low. The field relationships of the rocks as thin zones intimately interbedded with quartz-albite rocks points to a sedimentary origin. Possibly they were originally mixed aggregate clay minerals of the peculiar chemical composition noted heretofore and derived from mafic tuffs of El Carmen type.

Metacherts bear all the characters of normal chemically precipitated cherts. Some of the laminated quartz-albite granulites east of the morros of San Juan contain more albite porphyroblasts than most of the metacherts, possibly owing to the addition of feldspathic detritus to the original silica.

The basalt lavas and diorite which are best known east of the morros of San Juan (Pl. 2A) are considered to represent the end stages of the vulcanicity which attained its peak in El Carmen time.

The origin of the metadiorites is problematical. The sills southwest of La Puerta (Pl. 2A, D5-6) appear to interfinger with the porphyritic lavas and tuffs. Accordingly they were interpreted in the field as representing an intrusive facies of the lavas. The latter appear to be identical to the El Carmen lavas, a specimen of which gave a chemical analysis of a Na_2O-rich basalt (Table 1, column 5). The analysis of the diorite is entered in column 6 of Table 1. The difference between the two suggests that they are genetically unrelated. The metadiorite resembles Daly's (1933) average composition for diorite and andesite, but the Na_2O:K_2O ratio is higher than in the averages. The paucity of potassic minerals throughout the geologic section in the Central Aragua area suggests that the Na_2O-rich character of the metalavas and metadiorite is inherited from the original magmas, but there is no conclusive evidence on this point.

The metamorphic assemblage developed in the diorites is typical of the Villa de Cura group generally, and hence the intrusive mass is considered to have been emplaced before the main metamorphism which affected the Central Aragua area. The Tiara volcanic rocks are certainly younger and hence cannot be genetically related to the metadiorite.

Summation.—The Villa de Cura group (Fig. 2) consists of four formations. The El Caño, El Chino, and El Carmen formations form a sequence of basic lavas and tuffs which have undergone low-grade regional metamorphism. Lesser volumes of graphitic phyllite and quartz-albite granulites and schists suggest intervening episodes of deposition of nonvolcanic character. The uppermost (Santa Isabel) formation consists mainly of chlorite schists, quartz-albite granulites, and epidote-chlorite-quartz-albite schists. Some of these rocks contain glaucophane. The volume of volcanic rocks is minor. This formation lies probably conformably above the El Carmen formation.

The typical metamorphic assemblage is epidote, chlorite, quartz, albite, and amphibole. The last comprises both glaucophane and actinolite. These two minerals are considered to be the critical constituents for evaluation of the grade of the metamorphism. The significant relationships observed include the following:

(1) The proportion of glaucophane attains 30 per cent by volume in some rocks but is commonly in the range 2–6 per cent. Whether present in small or large amounts, the mineral always occurs as well-formed idioblastic crystals.

(2) Glaucophane was observed in the quartz-albite granulites, epidote-chlorite-quartz-albite schists, and the metadiorites of the Santa Isabel formation; in the chlorite-quartz-albite schists and the metatuffs of the El Chino sequence; in some of the El Carmen lavas; and in places in the El Caño volcanic rocks. The only compositional factor common to all these rocks is their high Na_2O:K_2O ratio. Attempts to recalculate these analyses to the typical greenschist assemblage of epidote-chlorite-albite indicate that there is a sufficiency of alumina and silica to convert all the Na_2O to albite: *i.e.*, the presence of glaucophane in these specific rocks cannot be related to an especially low Al_2O_3:Na_2O ratio.

(3) Bulk composition of the rocks, other than perhaps a high Na_2O–K_2O ratio, does not seem to be the controlling factor in the development of glaucophane. Small localized occurrences of glaucophanitic rocks have been reported from several areas. Taliaferro (1943) and Schürmann (1950; 1951; 1953) have shown that glaucophane in some terrains is related to ultramafic intrusions. These authors consider Na, Fe, and Mg metasomatism related to the ultramafic rocks to have been responsible for the formation of glaucophane. Dengo (1950) described small lenses of eclogitic and glaucophane amphibolites within the gneisses, quartz-muscovite schists, crystalline limestones, and calcareous mica schists of the Caracas group

in the vicinity of Caracas approximately 110 km northeast of San Juan de los Morros. Dengo suggests that the mineral assemblages developed (including glaucophane) are a metastable step in the change of mafic igneous rocks to stable assemblages in the greenschist or albite-epidote-amphibolite facies of regional metamorphism.

Such relationships as these were not observed in the Central Aragua area. Here the glaucophane-containing rocks occupy a broad belt more than 10 km wide. Glaucophane schists are of world-wide occurrence in regionally metamorphosed orogenic belts. In recent years they have been described by Brouwer and Eggeler in Corsica (1952) and by de Roever in the Celebes (1950). Schürmann (1953) has compiled from the literature their occurrence in Europe (both Alpine and Caledonian), Asia, Australia, and the Americas.

Whatever the fundamental control is in the formation of glaucophane, it cannot be ascribed to exceptional conditions in the physical or chemical environment other than in its general limitation to orogenic belts.

Brouwer and Eggeler (1952) on the basis of their work in Corsica suggested a glaucophane-schist facies of metamorphism and defined three subfacies. However, certain features of the Central Aragua occurrences are not in accord with this postulate.

(a) Fewer than 25 per cent of the Villa de Cura group specimens contain identifiable glaucophane. Possibly a considerably greater proportion contain the mineral as minute rods which are too small to identify positively in thin section. This then could be related to the short duration of the metamorphism.

(b) Commonly the most glaucophane-rich rocks (these are actually amphibolitic schists in which the mineral exceeds 30 per cent by volume) occur as thin tabular zones 1–10 m thick interbedded with glaucophane-free schists. The best examples were observed in the first ford of the Quebrada El Chino (Pl. 1, C11) and in the lower reaches of the quebradas Honda (Pl. 1, B16) and La Hermana (Pl. 1, E24-F25). These rocks are deep blue green and may be readily distinguished from the adjacent schists, which are medium green.

It is difficult to avoid the conclusion that bulk composition was the controlling factor in the formation of this amphibole, contrary to the conclusion in (2).

Because glaucophane occurs in a wide variety of rock types in the Villa de Cura group, the gross features of composition do not seem critical to its development. Its restriction to a small percentage of the beds of any given rock type in the sequence suggests some secondary chemical control based on proportions perhaps of minor constituents may be critical. Alternatively, it may be a metastable phase as is anthophyllite in the experimental work of Bowen and Tuttle (1949) on the MgO-SiO_2-H_2O system.

Actinolite is a common constituent but rarely exceeds accessory amounts. The mineral occurs as minute needles rarely exceeding 0.1 mm in length. In a few thin sections of quartz-albite schists from the Santa Isabel formation an amphibole transitional toward actinolite was observed. This mineral possesses pleochroism in shades of light green distinct from the colorless to pale-green pleochroism of actinolite. Amphibole with a bluish-green pleochroism apparently transitional toward glaucophane was also observed in a few specimens (*e.g.* Ar 466C). However, no true hornblendes of metamorphic origin were observed in the Villa de Cura group in the Central Aragua area.

All plagioclase (both porphyroblasts and crystalloblasts) is albitic. The metamorphism apparently never attained a grade sufficiently high to produce calc-aluminous amphibole or a more calcic plagioclase.

Textural characters observed in thin section suggest that most of the common phases were produced throughout the metamorphism. Glaucophane, actinolite, and chlorite are poikiloblastically enclosed by some albites and clearly replace others. Epidote commonly fringes and forms "tails" behind albite but is rarely enclosed by that mineral.

Clear narrow rims about the dusty cores of the albite porphyroblasts are common Phillips (1930), Brouwer and Eggeler (1952), and others have also reported these. The rims are considered to represent growth during the end stages or after the metamorphism.

The rocks of the lowest three formations of the Villa de Cura group were referred to in the petrographic descriptions as metatuffs and metalavas, whereas the Santa Isabel rocks were described as granulites and schists. This was because the three lowest formations retain many primary sedimentary characters, whereas the Santa Isabel does not. The reason for this difference is considered to be related to the difference in chemical composition and mechanical properties between the constituent rocks of the

formations. Under the grade of metamorphism which affected the Villa de Cura group apparently the rocks of the Santa Isabel formation were more amenable to reconstitution than those of the lower formations.

In summary, the rocks of the Villa de Cura group appear to have undergone low-grade regional metamorphism. The grade attained was not higher than that represented by the albite-epidote-amphibolite facies.

The writer was unable to determine the age relationship which the Villa de Cura group bears to the Caracas group. For the reasons presented in the section on correlation the group is considered to be one of the oldest units in the map area but younger than the Caracas group. It should be emphasized that this correlation has little positive evidence to support it and was determined largely by a process of elimination as to its possible position in the stratigraphic column.

The writer has found no descriptions in the literature of rock series of orogenic belts which are directly comparable to the Villa de Cura group.

The hornblende gneisses and quartz-plagioclase rocks described by D. B. MacKenzie (1953, unpub. Ph.D. thesis, Princeton Univ.) in the Tinaquillo area possibly represent the continuation along strike of the Villa de Cura group. These rocks consist essentially of blue-green hornblende, plagioclase in the range An_{10-30}, and quartz. The grain size is considerably coarser than that of the rocks described in this report. The Tinaquillo exposures possibly represent a deeper level of erosion of the Villa de Cura group and a higher grade of metamorphism. The Caracas group in MacKenzie's area also is present, somewhat more metamorphosed than in the region north of Villa de Cura.

Ultramafic Rocks

Within the map area are several serpentine bodies arranged along three subparallel lineaments. By far the most marked of these alignments begins west of Villa de Cura (Pl. 1, H1) as a small infaulted serpentine mass first mapped by MacLachlan (*in* MacLachlan, Shagam, and Hess, 1960) and continues eastward into the big Macuaya serpentine (Pl. 1, G4–5) and thence as smaller, commonly tabular masses along the valley of the Quebrada San Francisco to the Loma de Hierro mass north of Tiara (Fig. 1, N19–22). The last-named mass was investigated by Smith (1953) and is by far the largest body in this trend. This lineament continues as far east as Charallave (Hess, 1960, Fig. 2, H3). The Tinaquillo peridotite (Hess, 1960, Fig. 2, B4) described by MacKenzie (1960) is possibly the westerly continuation of this trend. In the Central Aragua area these serpentines occur along a major fault zone that forms the northern boundary of the Paracotos formation.

A second alignment of serpentine bodies follows the fault that marks the contact between the Paracotos and El Caño formations. The largest mass occurs immediately east of the Hacienda Agua Fria (Pl. 1, K20). Most of the serpentines in this group are very small and cannot be represented on the scale of Plate 1 (*See* Pl. 1, I8–9). To the west this trend ends against the Macuaya serpentine mass.

In essence these two serpentine lineaments mark major tectonic features along the northern and southern boundaries of the Paracotos formation. The concentration of serpentinites in the two lineaments, their obvious relationship to fault zones, and the small volume of many of the intrusive bodies suggest that both lineaments are related to a single sheet or sill of serpentine that existed at a shallow depth and that was later cut and displaced as a result of faulting. A certain amount of reinjection of the serpentinites took place along the fault zones as a result of compression during later deformations. The Macuaya mass which completely occupies the area between the two faults may possibly represent a part of the original sill now exposed at the surface. The significance of this postulated sheet of serpentine will be discussed in the section on correlation of formations.

A third serpentine belt occurs on or just outside the southern boundary of the map area. Small bodies crop out near Cumbre (Pl. 1, A12) and in a road cut near the Quebrada La Hermana road bridge (Pl. 1, A22). Several small masses crop out in road cuts between the Cumbre exposures and a point about 300 m south of the southern police post outside San Juan de los Morros (outside map area). The large ultramafic intrusive body south of the Hacienda El Chacao (Pl. 1, A1–5) has a mineralogic composition distinctly different from any of the serpentinites in the map area and is probably of independent origin. The location, size, and contact relationships of the serpentinites in this trend suggest that they are also upfaulted and reinjected portions of a sheet of serpentine located at shallow depth. Such a

sheet could conceivably be the same one as that postulated to explain the northern occurrences or could represent an independent intrusion.

In every case where contact relationships were observed the serpentinites of all three lineaments were in fault contact with the country rock. In a general way the ultramafic rocks are concordant with the structure of the country rock.

PETROGRAPHY: The serpentines may be recognized from afar by the paucity of vegetation or by the development of a short blue-green grass. In several places, notably the eastern part of the Macuaya mass, good fresh outcrops were found.

The rock is commonly medium to dark green and displays a marked resinous luster. In the large massifs the serpentine displays a blocky structure. This is related to a multiplicity of joints, faults, and fractures which trend in several directions. The thin tabular masses, on the other hand, are markedly schistose, the foliation paralleling the walls of the mass. Slickensides on these foliation planes are ubiquitous.

Most of the specimens examined were collected from the Macuaya mass. In thin section the rock is seen to consist of euhedral olivine relicts now existing as chrysotile serpentine, although occasionally the cores are fresh olivine. Small amounts of interstitial anhedral augite and plagioclase are also present. The latter has been converted to a brownish isotropic material. Some specimens consist of a reticulate arrangement of platy antigorite. In these sections large crystals of orthopyroxene in process of conversion to bastite were observed. Occasional veinlets of cross-fiber chrysotile and of chlorite are present in some sections. Estimates of the relative proportions of relict olivine and pyroxene suggest that these rocks were originally peridotites of dunitic to harzburgitic composition.

The El Chacao mass is petrographically unique. The rock is an olivine pyroxenite. Augite constitutes about 80 per cent by volume (a Rosiwal analysis of Ar 1707 gave the proportion of augite:olivine as 82:18) and occurs as unaltered euhedral to subhedral grains which average about 1.5 mm in diameter. Olivine (20 per cent) occurs only as anhedral grains interstitial to augite. The mineral is normally fresh, but grain margins are not uncommonly serpentinized. Local serpentinized zones occur throughout the pyroxenite, but in most exposures the rock is unaltered, in this respect only resembling the Tinaquillo intrusion.

AGE AND CORRELATION: The absence of contact-metamorphic features in the country rock adjacent to the ultramafic bodies and the consistently faulted nature of the contacts indicate that these masses have attained their present location in the crust as a result of postintrusive tectonism. In several places the serpentinites are faulted against Paleocene sedimentary rocks (south of the Macuaya mass, Pl. 1, G5, and southeast of San Juan de los Morros). Evidently this solid reintrusion of the ultramafic bodies took place during the late or post-Paleocene deformation that affected this region.

The age of original intrusion is more difficult to define. The fragmentary evidence available is as follows:

(1) Smith (1953) described a small serpentine intrusion in the Paracotos formation near Charallave (Hess, 1960, Fig. 2, H3). His thin sections indicate that the country rock may better be assigned to the middle Cretaceous Tucutunemo formation. This suggests a post-middle Cretaceous age for the serpentines. D. B. MacKenzie (1960) demonstrated intrusive relationships in the Tinaquillo area, but the hornblende-plagioclase country rock (equals, possibly, writer's Villa de Cura group) is itself of unknown age.

(2) Hess informs the writer that chromite is a common heavy mineral in the Coniacian Arrayanes formation. Presumably this mineral was derived from the ultramafic rocks. This suggests an upper age limit for these masses.

(3) Hess, Dengo, and Smith (1952) noted that the serpentinites presently occurring in low-grade schists in the southern portion of the metamorphic zone consist largely of chrysotile, whereas the ultramafic bodies in the higher-grade schists near Caracas consist almost entirely of antigorite. MacKenzie noted that enstatite phenocrysts in the Tinaquillo dunite have been deformed and oriented parallel to the lineation developed in the host-rock hornblende gneisses. Apparently the ultramafic rocks were intruded prior to or during the main period of metamorphism and deformation. Elsewhere in this report evidence is presented to show that this deformation took place in middle to early Late Cretaceous time.

These admittedly tenuous arguments suggest a middle to early Late Cretaceous age for the original intrusion of the ultramafic masses.

COMPARISON TO OTHER VENEZUELAN SERPENTINITES: The serpentine masses north and west of Caracas described by Dengo (1953) have already been mentioned. These display the same structural and morphologic characters as the Central Aragua serpentinites, but the dominant serpentine mineral is antigorite. Six small bodies were described by Smith (1953) from the area west of San Pedro (Hess, 1960, Fig. 2, G2). In these masses chrysotile is the

dominant phase. However, most information concerning Venezuelan ultramafic rocks has stemmed from the extremely detailed and careful study performed by D. B. MacKenzie (1960) on the Tinaquillo peridotite mass (Hess, 1960, Fig. 2, B4). This mass is largely unserpentinized and consists of dunite with lesser amounts of harzburgite. The absence of serpentinization is possibly related merely to a greater depth of erosion in the Tinaquillo area as compared to the Central Aragua area. From the nature of the pyroxene minerals and the contact metamorphism, MacKenzie was able to suggest a temperature of intrusion between 800° and 1000°C.

Younger Metamorphic Complex

Tiara Volcanic Formation

The younger metamorphic complex includes the Tiara and Paracotos formations. The former is dominantly a volcanic sequence, whereas the latter is of sedimentary origin. The rocks of these formations were deposited after the main period of deformation but before the much weaker deformation that began in Late Cretaceous time.

Smith (1953, p. 58) named an occurrence of basaltic rocks for the village of Tiara (Pl. 1, N21; Hess, 1960, Fig. 2, G3), near which good exposures of these volcanic rocks were observed. MacLachlan, Shagam, and Hess (1960) show that two distinct volcanic sequences were included by Smith in this formation. The older sequence, which crops out in the Tacata-Charallave area (Hess, 1960, Fig. 2, H3), should probably be correlated with the Los Naranjos volcanic rocks of MacLachlan, Shagam, and Hess and predates the main metamorphism. In this report, the term Tiara volcanic rocks refers to the younger sequence which postdates the main metamorphic period. It is the younger sequence which crops out at the type locality of Tiara defined by Smith, and hence the name is retained.

Within the map area the Tiara volcanic rocks crop out in several localities. The most extensive and freshest exposures occur north of San Sebastián (Pl. 1, C17 to B25). Two small poor exposures are located on the south side of the morros of San Juan (Pl. 2A, C3–D3). A similar example of Upper Cretaceous or Paleocene rocks lying on Tiara lavas forms a low hill on the southern edge of Villa de Cura (Pl. 1, G2). In this occurrence a small volume of basaltic pillow lava was found. Several small exposures of the volcanic rocks are located on a line that extends from the upper reaches of the Río Tucutunemo along the valleys of the quebradas San Francisco and Paito to Tiara (Pl. 1, K13 to N19). The small occurrence at Villa de Cura and those scattered outcrops along the northern boundary of the map area as far east as Tiara were first mapped and described by MacLachlan.

The gabbroic and diabasic facies of the Tiara volcanism occur most abundantly in the northern part of the map area, whereas the volcanic conglomerates associated with the lavas attain their greatest volume in the exposures north of San Sebastián. It is likely that the original volcanic centers were controlled by the major structural fracture marked by the line of serpentine intrusions along the Santa Rosa fault and that the lavas flowed out to cover the present area of outcrop of the Villa de Cura group. No information is available as to the southern limits of distribution of the lavas under the cover of unmetamorphosed Late Cretaceous and Tertiary rocks. The thickness of lavas must at one time have been considerable, for they supplied by far the largest proportion of detritus to the younger sedimentary formations. The minimum thickness of the volcanic rocks exposed is not less than 400 m.

The bottom contact of the formation is everywhere obscured by faulting or a thick cover of alluvium, except north of San Sebastián where it overlies unconformably the Santa Isabel formation. The Tiara exposures at Villa de Cura, under the morros of San Juan, and west and east of San Sebastián are overlain disconformably by unmetamorphosed sedimentary rocks of Maestrichtian to Paleocene age. Renz (1955) found lavas (nature unspecified) intercalated with these sedimentary rocks, but the writer did not observe them. In the vicinity of Tiara the contact of the volcanic rocks with the slightly metamorphosed Maestrichtian Paracotos formation is a fault.

The Tiara volcanic rocks comprise a series of basalt flows and associated volcanic conglomerates and tuff beds with some gabbroic and diabasic intrusive facies. The writer has examined hand specimens and thin sections from all the localities listed heretofore. Grain size and relative proportion of phenocrysts to groundmass vary considerably, but throughout the area certain constant textural and mineralogic characters are present which distinguish these rocks from the volcanic rocks of the Villa de Cura group. These diagnostic characters

TABLE 2.—COMPARISON OF THE LAVAS OF THE EL CARMEN AND TIARA FORMATIONS

		El Carmen	Tiara
Hand specimen		Distinctive bluish-green rock with spotted appearance related to the presence of dark-green augite phenocrysts. Vesicles rare. Moderate metamorphic foliation	Medium-green rock. Markedly vesicular in patches. Spotted appearance related to presence of augite and plagioclase phenocrysts. Fractured but rarely foliated
Thin section	Augite	Phenocrysts: Large stumpy prismatic grains. Unaltered. Commonly zoned. Rarely less than 10 per cent by volume Groundmass: Euhedral prismatic grains and anhedral granules. Completely unaltered. Commonly 10–20 per cent by volume	Large stumpy prismatic grains; uncommonly altered to chlorite, epidote, actinolite. Rarely exceed 3 per cent by volume; commonly absent Stumpy subhedral grains normally altered to chlorite, epidote, actinolite. About 30 per cent by volume
	Plagioclase	Phenocrysts: Rare relict saussuritized tablets of plagioclase Ground-mass: Not observed	Euhedral tablets of albite common; 5–15 per cent by volume. Saussuritized calcic grains present in many specimens Euhedral microlitic laths of albite are distinctive feature of the rock, 45 per cent by volume
	Opaque minerals	Rare magnetite octahedra	Microphenocrysts of titaniferous magnetite are striking; 5–10 per cent by volume
	Other minerals	Minute crystalloblasts of chlorite and actinolite and ragged porphyroblasts of albite constitute the bulk of the rock. Minor epidote and glaucophane also present. All are of metamorphic origin. Minor calcite; replaces all other minerals	Chlorite, actinolite, epidote are hydrothermal or deuteric alteration products of primary minerals. No metamorphic minerals present. Calcite fills vesicles and replaces all other minerals
Texture		Unaltered augite phenocrysts (15 per cent) and microphenocrysts (10–20 per cent) in a groundmass consisting of a complex intergrowth of actinolite, chlorite, and albite. No ophitic or subophitic relationships were observed	Phenocrysts of augite (0–3 per cent) and plagioclase (commonly albite; 5–15 per cent) in a groundmass consisting of microlitic albite laths (45 per cent) subophitically related to augite (30 per cent). The groundmass augite has been completely altered to chlorite, actinolite, and epidote. Microphenocrysts of titanomagnetite constitute 5–10 per cent. *See* Figure 4 of Plate 5.

are presented in the rock descriptions and in Table 2.

Petrography

LAVAS (Pl. 5, fig. 4):

Macroscopic characters: Medium-green, fine-grained rocks with a spotted appearance related to the presence of large green phenocrysts of augite and white pheocrysts of plagioclase and to large calcite-filled vesicles. Despite the common occurrence of pillow structure the writer was rarely able to determine the structural attitude of the lavas. Metamorphic foliation was not observed, but fracturing is not uncommon. The absence of metamorphic structures is in direct contrast to the lavas of the El Carmen formation.

Microscopic characters: Plagioclase: phenocrysts. Large stumpy and elongate euhedral crystals as much as 5 mm long, commonly 1 mm. Several size fractions down to microphenocrysts occur. Commonly the grains are in glomeroporphyritic groups of 3 to 10 grains. Plagioclase phenocrysts may constitute as much as 50 per cent by volume of the rock, usually in the range 5–15 per cent.

Replacement by chlorite, actinolite, and calcite results in embayed grain margins. The replacement has gone to completion in some specimens. In some cases only completely saussuritized plagioclase occurs (*e.g.*, Ar 1511, Ar 416; V347 [Hess]); in most specimens a plagioclase whose only alteration is a brownish turbidity and the saussuritized variety both occur as phenocrysts. The turbid plagioclase is albite (from index of refraction measurements); the other probably represents a primary calcic plagioclase. Zoned crystals were infrequently observed and are marked by variation in the degree of alteration from zone to zone.

Augite: phenocrysts. Large stumpy euhedral crystals up to 1 cm long, commonly 0.5–1.0 mm, which constitute as much as 10 per cent by volume of the rock, normally less than 3 per cent. More than one generation of augite is usually present; the smallest are microphenocrysts. In some specimens the augite phenocrysts are fresh, in others they are altered to chlorite and actinolite. Fresh and altered grains commonly occur in the same thin section. There is no correlation between the alteration of the plagioclase grains and that of the augite. In many specimens calcite has replaced the augite phenocrysts partially or totally.

Titanomagnetite: Phenocrysts. Microphenocrysts commonly 0.1 mm in diameter are characteristic of nearly all specimens. They constitute 5–10 per cent by volume of the rock. Alteration to leucoxene or sphene is common.

Olivine: phenocrysts. Very rarely serpentine and chlorite replace phenocrysts apparently pseudomorphous after olivine. No positive identification of olivine was made.

Plagioclase: groundmass. Elongate bent microlitic laths generally exceeding 0.1 mm in length. The grains display a brownish turbidity, but none are saussuritized. Refractive-index measurements indicate an albitic composition. They constitute 30–60 per cent by volume of the rock.

Augite: groundmass. Anhedral to subhedral grains with few exceptions altered to chlorite, actinolite, and common epidote. They are commonly 0.05 to 0.3 mm in diameter. Groundmass augite constitutes 20–40 per cent by volume of the rock.

Texture: Phenocrysts of plagioclase, commonly glomeroporphyritic (5–15 per cent), and augite (3 per cent or less) occur in a fine-grained groundmass composed of altered augite grains (30 per cent) subophitically related to microlitic plagioclase laths (45 per cent). Microphenocrysts of titanomagnetite (5–10 per cent) are evenly distributed throughout the groundmass. Uncommonly the phenocrysts display a subophitic relationship, too.

Name: Porphyritic basalt

INTRUSIVE FACIES:

In hand specimen these appear to be normal, but light-colored, diabasic rocks. In thin section the mineralogy is seen to be the same as that described for the lavas. There are large subhedral to euhedral plates of augite ophitically and subophitically related to elongate tabular grains of plagioclase which are commonly completely saussuritized. Skeletal remains of titanomagnetite octahedra are present in amounts up to 5 per cent by volume of the rock. Some alteration of the augite to actinolite and chlorite has taken place.

SEDIMENTARY ROCKS:

Associated with the lavas are graded bedded sandstones and conglomerates composed of the same volcanic material. The constituent pebbles are well rounded and are hence considered to be ordinary sedimentary rocks, rather than tuffs. In the most southerly exposures of the volcanic rocks in the quebradas La Hermana and Chupadero there are outcrops of boulder conglomerate containing rare boulders of a light-gray-blue fine-grained limestone, flecked with dark-gray slivers of shaly material. These limestone fragments are unlike any limestones of the older formations. They are possibly derived from coral reefs fringing the original volcanic centers.

CHEMICAL AND MINERALOGIC CHARACTERS: The only available chemical analysis of Tiara lava (Smith, 1953, p. 58) appears to be that of an olivine basalt unusually rich in K_2O (2.58 per cent). The analysis is suspect in that no potassium-rich minerals were observed in thin section, and little was brought out by sodium cobaltinitrite staining (Chayes, 1952). Moreover the Na_2O content (1.06 per cent) is too low to account for the albitic plagioclase content which makes up at least 40 per cent by volume of the rock.

The amount of albite present suggests a spilitic composition, but whether this is a primary feature of the magma is unknown. The mineralogic evidence is inconclusive. Saussuritized feldspar in the lavas indicates that some of the primary plagioclase was of calcic nature. The widespread occurrence of calcite replacing albite phenocrysts suggests that the albite may be the product of deuteric or hydrothermal alteration of calcic plagioclase. On the other hand the microlitic albite laths of the groundmass have every appearance of being primary products of crystallization. With one exception all specimens of the intrusive facies contain saussuritized plagioclase only, to the exclusion of albite. This is the strongest indication that the present mineral assemblage of the lavas represents albitization of an originally normal basaltic rock.

The present state of the constituent minerals merits comment. Reference has been made to the consistently fresh character of the augite phenocrysts and groundmass augite prisms in the El Carmen spilitic metabasalts. In the Tiara lavas most of the augite phenocrysts are fresh or only slightly altered. Completely altered phenocrysts were infrequently observed and then in the same thin section as fresh grains. The groundmass pyroxene, however, is commonly completely altered to actinolite, chlorite, or common epidote. In rare cases the groundmass pyroxene is altered in part only (Ar 511) or not at all (Ar 413).

In both volcanic sequences the albite displays a brownish turbidity but is otherwise unaltered, whereas calcic plagioclase is completely saussuritized. The actinolite and chlorite of the Tiara lavas is clearly pseudomorphous after augite, whereas in the El Carmen volcanic rocks they are independent deuteric or metamorphic products.

The reason for this variable resistance to alteration in the two volcanic formations is unknown. An evaluation of the mineralogic data is complicated by the fact that the El Carmen volcanic rocks were involved in the main metamorphism, whereas the Tiara lavas were not. Further, the two sequences are not isochemical systems.

METAMORPHISM: The Tiara volcanism took place after the main metamorphism which affected the Caracas and Villa de Cura groups, but the rocks were involved in the later, weaker, Late Cretaceous-Paleocene deformations. Accordingly they display minor fracturing and folding only. There is no constant metamorphic foliation as is so well developed in the El Carmen volcanic rocks. There is no evidence to suggest that the alteration of the groundmass pyroxene and plagioclase is other than the result of deuteric or hydrothermal activity. Why the augite phenocrysts should have escaped such alteration is unknown.

AGE AND CORRELATION: Pebbles of Tiara lavas are common in the Arrayanes formation, which is known to be Coniacian. The Tiara formation was not affected by the main episode of metamorphism. It unconformably overlies the metamorphosed rocks of the Villa de Cura group. No diagnostic fauna has been obtained from the limestone boulders found in some of the Tiara volcanic conglomerate outcrops. The formation is thought to be early Late Cretaceous. The considerations are elaborated in the section on correlation of formations.

Paracotos Formation

The name Paracotos formation was proposed by Smith (1953, p. 52) to include a succession of phyllites, metatuffs, and metagraywackes which he considered to lie unconformably above the Caracas group. The formation was named for the village of Paracotos (Hess, 1960, Fig. 2, H2), where a good partial section was observed. The writer believes that a part of the total succession defined by Smith is better relegated to the Tucutunemo formation and proposes that the name Paracotos formation be restricted to the upper Paracotos of Smith, which crops out near Paracotos.

Rocks of this formation form a narrow band along the northern boundary of the map area. The dominant rock type of the Paracotos formation (about 60 per cent of the total thickness) is a blue carbonaceous silty phyllitic shale. Unlike the Tucutunemo phyllites this rock practically nowhere ranges to a sandy facies. Throughout the phyllites are thin lenticular bodies of gray and pale-green aphanitic limestone. At one stratigraphic level, close to the top of the exposed succession, such a limestone member exists with a continuity far exceeding that of lenses lower in the sequence. This zone, although in places discontinuous, constitutes a prominent marker unit.

Closely associated with the uppermost gray limestone is a striking gray-green conglomerate composed largely of mafic volcanic pebbles. It is best developed below the limestone but in

some places is repeated above that member. The conglomerate is of variable thickness (2–100 m) and is not continuous; the discontinuities in outcrop are smaller and less common than those of the limestone zone. This association of conglomerate and limestone is unique in the Paracotos formation; hence the uncommon green limestones at lower horizons cannot be mistaken for the marker unit. In two traverses south of the serpentine intrusion on the Hacienda Las Vagres (Pl. 1, I7-8) the same type of conglomerate was found at a much lower stratigraphic level. These are the only places where the conglomerate was found at horizons other than the uppermost marker unit.

Minor volumes of a dark-blue fine-grained limestone and a black carbonaceous siltstone occur as thin (2–20-cm thick) zones throughout the phyllite sequence. Although of minor volume, these two rock types are characteristic of the Paracotos formation. Some thin beds of sandstone were also observed.

The exact thickness of the formation is unknown, as both the top and bottom contacts are faults. The minimum thickness is estimated at 400 m.

Petrography

GRAY-GREEN LIMESTONE (Pl. 6, fig. 1):

Macroscopic characters: Very pale-green or light-gray to bluish-gray aphanitic rock. In some outcrops the limestone is submassive; in others a strong platy foliation is developed. The limestone occurs as lenses as much as 100 m thick (commonly 5–10 m) throughout the stratigraphic succession. One lens measures about 3 km along the strike; most are less than 500 m long. In several instances the rock forms prominent cliffs on hill slopes; the outcrop at I12 on Plate 1 forms a particularly prominent morro.

The pale-green variety is commonly found in the lower to middle portions of the formation; the gray variety forms a discontinuous but prominent marker unit close to the top of the exposed sequence. The limestone is well bedded in massive units 5–20 cm thick. A faint microfoliation parallel to the major bedding is not uncommon. The limestones constitute about 10 per cent of the total thickness of the formation.

Microscopic characters: Small spherical Foraminifera now replaced by minute calcite rhombs are dominant in thin section. The groundmass is composed of a very fine-grained aggregate of calcite crystals less than 0.03 mm in diameter. Small, highly embayed quartz grains devoid of inclusions and bubble trains constitute 1–3 per cent by volume of the rock. Small cubes of pyrite are rare; shreds of carbonaceous material and iron ores occur along foliation planes, usually in accessory amounts.

Texture is determined by the proportion of fossils present. Ar 627 is a foraminiferal limestone with minor calcite matrix. Ar 744 is a very fine-grained equigranular rock composed of minute calcite rhombs with scattered Foraminifera. Rarely a faint metamorphic foliation is revealed by a slight flattening of the fossils parallel to the foliation planes.

Name: Aphanitic foraminiferal limestone

GRAY-GREEN CONGLOMERATE:

Macroscopic characters: A gray-green bedded rock containing boulders as much as 50 cm in diameter, more commonly pea-sized pebbles. With rare exceptions the conglomerate is restricted to a thin zone at the top of the formation, usually immediately below the uppermost gray limestone zone. Not uncommonly it is repeated above the latter, too. This member may be as much as 100 m thick, more usually 30 m. It constitutes about 5 per cent of the total thickness of the formation. Among the best and most accessible exposures are those in the upper reaches of the Río Caramacate (Pl. 1, L20).

In many outcrops the rock exhibits excellent graded bedding in units 20–50 cm thick. Metamorphic structures are uncommon; in some outcrops pebbles are stretched out parallel to the strike of the bedding. The finest-grained facies is highly chloritic and has developed a moderate foliation.

Microscopic characters: Pebbles: Lava pebbles, superficially varied, but with significant characters in common to suggest a single basaltic source, are the dominant constituents. These are commonly very fine-grained rocks with a matrix of minute intersertal plagioclase laths enclosing tabular phenocrysts of saussuritized plagioclase. Some have a doleritic texture of subhedral augite (altered to pale-green amphibole) subophitically related to tabular plagioclase grains. Microphenocrysts of titaniferous magnetite are abundant in all these pebbles. Variations observed concern mainly grain size. On lithologic grounds these pebbles are considered to be derived from the basalts of the Tiara volcanic formation. The lava pebbles form about 60 per cent by volume of the rock.

Other constituents (10–30 per cent by volume of the rock) include vein-quartz pebbles, fine-grained equigranular pure limestone, sandy limestone (angular quartz 25 per cent, albite 10 per cent), fine-grained crystalline chert, and quartz-albite granulite very similar to that of the Santa Isabel formation (rare). Some pebbles are too fine-grained or altered for identification.

Matrix: forms 10–30 per cent of the volume of the rock and consists of large imperfect calcite rhombs (0.3–0.6 mm in diameter) with lesser amounts of angular quartz and albite grains and uncommon altered plagioclase, augite, and amphibole grains.

Texture: Well-rounded ellipsoidal pebbles (70–90 per cent) occur in a calcareous matrix. Commonly the rock and its constituent pebbles display no postdepositional metamorphic effects. Uncommonly the pebbles have been flattened, as seen where a pebble has been molded onto its neighbor (*e.g.*, Ar 315).

SANDSTONES:

Interbedded with the phyllitic shales are thin beds (10–50 cm thick) of bluish-gray sandstone. The sandstones constitute about 5–10 per cent of the total thickness of the formation. Thin-sections show two dominant varieties:

(1) An equigranular rock (grains average about 0.1 mm in diameter) composed of angular quartz grains (65 per cent), perfect rhombs of calcite (25 per cent), and unoriented flakes of muscovite (5–10 per cent) with accessory tourmaline and zircon.

Name: Calcareous micaceous sandstone

(2) A poorly sorted rock composed of subrounded rock fragments (including mafic lava pebbles) (20 per cent) and angular quartz (55 per cent) and albite (5 per cent) grains in a fine-grained quartz-rich matrix (15 per cent). The pebbles and large grains are generally in mutual contact at points, leaving triangular matrix areas. A few specimens have very little matrix; in others the grains are entirely enclosed by matrix. The accessories are ore minerals, calcite, muscovite, tourmaline, and zircon (the last two are rare).

Name: Quartzose lithic wacke

BLACK SILTSTONE:

Macroscopic characters: Jet-black, aphanitic, bedded rock. The siltstone occurs as thin (2–8-cm) beds in the phyllites, forming small but prominent ribs in stream outcrops. Minute quartz-calcite veins parallel to the dip direction are ubiquitous. The rock is notably massive compared to the phyllites, but a faint metamorphic foliation parallel to bedding is discernible. Large pyrite cubes are commonly concentrated in the middle of the beds. The rock constitutes less than 5 per cent of the total thickness of the formation.

Microscopic characters: Under the highest magnification (×400) only the following features were noted. Minute embayed quartz grains commonly less than 0.03 mm in diameter constitute the commonest mineral species. Minute perfect rhombs of dolomite (?) up to 0.03 mm in diameter but usually less than 0.02 mm replace the quartz and make up approximately 15 per cent by volume. There are also minute spherical opaque grains in lines, irregular blebs, and spaced clusters; these are in part ore minerals and in part carbonaceous material. Large pyrite cubes are common. They are usually restricted to the central portion of the beds. The rock appears to be similar in composition and texture (but much finer-grained) to type 1 of the sandstones described heretofore.

Name: Carbonaceous dolomitic quartzose siltstone

PHYLLITIC SHALE:

Macroscopic characters: Dark-gray-blue, aphanitic, foliated rock which weathers to a soft light-gray clay. This rock type constitutes about 60 per cent of the total thickness of the Paracotos formation. Rarely, bedding is suggested by faint sorting in grain size over a thickness of 1 cm. Where the intercalations of the black siltstone, sandstone, or limestone occur, the metamorphic foliation is clearly seen to be parallel to original bedding. The intersection of this foliation with vertical joints parallel to the strike results in commonly brittle pencillike fragments. Small gentle folds of radius up to 3 m are common. These and the weak microfold lineation that is developed trend parallel to strike, commonly plunging gently either to east or west.

Microscopic characters: Minute grains of quartz, dolomite (?), volcanic fragments, and flakes of white mica (largely detrital) were observed, but their relative proportions are unknown. The rock appears to have a markedly even and fine-grained texture. Variations to sandy facies as in the Tucutunemo phyllites are almost unknown. Scattered throughout the phyllite are rare boulders as much as 20 cm in diameter of volcanic and sedimentary rocks. Commonly these are the same as those seen in the gray-green conglomerate. One specimen of biotite-quartz andesite was found.

Name: Phyllitic shale

The limestone-conglomerate association in a phyllitic sequence is common to both the Paracotos and Tucutunemo formations. While this suggests similarity in the depositional environment the actual rock types are distinctly different, and the two sequences constitute distinct formations. The lithologies of the two formations are compared in Table 3.

DEPOSITIONAL ENVIRONMENT: Both the phyllites and the intercalated sandstones are notably well sorted and imply a marine basin of deposition of shallow to moderate depth—that is, one exposed to the sorting processes operative within wave base. Locally, in small basins free of sedimentation, the green limestone member would be chemically precipitated as a calcareous mud.

The close association of the gray-green conglomerate and the gray limestone suggests that they are products of a consanguineous depositional environment. The wide distribution and persistence of these rocks indicates that this environment prevailed throughout the region. The common occurrence of graded bedding in the conglomerate could be related to subaqueous mass movement of detritus set

in motion by a sudden tectonic disturbance of widespread distribution but minor character. However, it is difficult to reconcile such an gray-green conglomerate uncommonly displays pebbles stretched-out in the direction of strike.

Throughout the sequence microfold lineation

TABLE 3.—COMPARISON OF THE LITHOLOGY OF THE PARACOTOS AND TUCUTUNEMO FORMATIONS

	Paracotos formation	Tucutunemo formation
Phyllite	Blue carbonaceous rock; originally siltstone; variations to sandy facies rare	Blue carbonaceous rock; originally siltstone; variations to sandy facies common
	White mica largely of detrital origin; little of metamorphic origin *in situ*	White mica dominantly of metamorphic origin *in situ*
	Thin (2–8 cm) intercalations of massive jet-black siltstone	No black siltstone
	Metamorphic textures and structures weakly developed. Essentially phyllitic shales	Prominent development of metamorphic textures and structures. Essentially phyllitic schists
Limestone	Pale-green, light-gray, gray-blue, aphanitic rock of uniform appearance	Dark-gray, black aphanitic rock of spotted appearance related to weathering out of large quartz and calcite grains
	No clastic calcite grains	Prominent clastic calcite grains
	Rare angular quartz grains	Embayed quartz and albite grains, 3–30 per cent by volume of rock
	Abundant fairly well-preserved Foraminifera	Rare fossil fragments
	Weak metamorphic foliation	Prominent metamorphic foliation
	A foraminiferal limestone	A quartzose crystalline limestone
Conglomerates	Gray-green rock; well-developed graded bedding	White to light-gray rock; poorly sorted
	Dominance of basalt pebbles derived from Tiara volcanic rocks	No basalt pebbles
	Minor amounts of vein quartz, limestone, black crystalline chert, and quartz-albite granulite pebbles	Dominant vein quartz and quartz-plagioclase (granite ?) pebbles. Minor black crystalline chert and quartz-albite granulite pebbles
	Metamorphic textures and structures poorly developed	Prominent development of metamorphic textures and structures (Boehm lamellae, mortar structure
	Resemble Arrayanes conglomerates	Resemble Las Mercedes conglomerates

environment with that necessary for the deposition of the gray limestone. The aphanitic character of the limestone and the paucity of detrital grains suggest quiet conditions during which it was precipitated from sea water as a calcareous mud.

METAMORPHISM: The characteristic features of the rocks indicate that they underwent regional metamorphism of the lowest grade. The phyllites show a poor development of white mica. The gray and green limestones contrast markedly with the limestones of the Tucutunemo formation in having very fine grains and well-preserved microfossils. The parallels the strike of the foliation, but with rare exceptions it is weakly developed.

These metamorphic characters reflect a weaker grade of metamorphism than that which affected the Tucutunemo formation. The significance of this fact will be remarked in the section on correlation.

AGE AND CORRELATION: The gray limestone of the Paracotos formation is highly fossiliferous in some outcrops. Specimens were submitted for paleontological analysis to Drs. H. H. Renz of the Mene Grande Oil Company, A. N. Dusenbury of the Creole Petroleum Corporation, and P. Bronnimann of the Cuban Gulf

Oil Company. All agreed on a Maestrichtian age for these specimens. Excerpts from a report prepared by Dusenbury follow.

Ar 305. Dark-gray, microgranular to microcrystalline, graphitic, schistose limestone cut by rare veins of white calcite up to 0.2 mm in thickness. Rare pyrite in cubic crystals. Schistosity strongly developed. Foraminifera abundant, recrystallized, distorted, usually so poorly preserved as to be unidentifiable.

Foraminifera
Guembelina globulosa (Ehrenberg), Turonian to Maestrichtian (F)
Neobulimina sp. (R)
Globigerina cretacea d'Orbigny, Cenomanian to Maestrichtian (F)
Globigerinella messinae messinae (Bronnimann), Maestrichtian (F)
Plummerella hantkeninoides (Bronnimann), Maestrichtian (R)
Globotruncana sp. (R)
Planulina? sp. (R)
(F, flood; A, abundant; S, scarce; R, rare)
Age: Maestrichtian

Ar 307. Gray, foraminiferal, microgranular, schistose limestone. Schistosity weakly developed. Foraminifera extremely abundant, forming approximately half of the sample; recrystallized but only occasionally distorted, many unidentifiable.
Foraminifera
Guembelina globulosa (Ehrenberg), Turonian to Maestrichtian (A)
Guembelina glabrans Cushman, Maestrichtian (R)
Buliminella? sp. (F)
Bulimina prolixa Cushman and Parker, Turonian to Maestrichtian (R)
Globigerina spp. (A)
Rugoglobigerina rugosa? (Plummer), Turonian to Maestrichtian (R)
Rugoglobigerina macrocephala? Bronnimann, Turonian to Maestrichtian (R)
Globigerinella messinae messinae Bronnimann, Maestrichtian (A)
Globotruncana citae Bolli, Campanian and Maestrichtian (S)
Globotruncana gansseri Bolli, lower Maestrichtian (S)
Eouvigerina americana Cushman, Coniacian to lower Maestrichtian (R)
Globotruncana stuarti (de Lapparent), Campanian and Maestrichtian (R)
Age: Maestrichtian

Ar 627. Dark-gray, foraminiferal, microgranular, schistose limestone. Schistosity well developed. Limestone cut by thin veins of iron oxide which are in turn cut by veins of white calcite up to 0.1 mm in thickness. Foraminifera extremely abundant, forming about 65 per cent of the sample; recrystallized but only occasionally distorted, many unidentifiable.

Foraminifera
Robulus? sp. (R)
Nodosaria affinis Reuss, Coniacian to Paleocene (R)
Guembelina globulosa (Ehrenberg), Turonian to Maestrichtian (A)
Guembelina plummerae Loetterle, Turonian to Maestrichtian (S)
Buliminella sp. (R)
Neobulimina sp. (R)
Globigerina cretacea d'Orbigny, Cenomanian to Maestrichtian (A)
Globigerina spp. (A)
Globigerinella messinae messinae Bronnimann, Maestrichtian (A)
Plummerella hantkeninoides Bronnimann, Maestrichtian (R)
Globotruncana citae Bolli, Campanian and Maestrichtian (S)
Globotruncana gansseri Bolli, lower Maestrichtian (S)
Globotruncana lapparenti Brotzen, Turonian to Campanian (R)
Stilostomella? sp. (R)
Age: Maestrichtian

Ar 751. Dark-gray, microgranular to microcrystalline, argillaceous, schistose limestone cut by veins of white calcite up to 8 mm in thickness. Schistosity strongly developed, especially in the more argillaceous layers. Foraminifera abundant, recrystallized, usually distorted and so poorly preserved as to be unidentifiable.

Foraminifera
Guembelina globulosa (Ehrenberg), Turonian to Maestrichtian (A)
Neobulimina sp. (R)
Globigerina cretacea d'Orbigny, Cenomanian to Maestrichtian (A)
Globigerina spp. (A)
Globigerinella messinae messinae Bronnimann, Maestrichtian (F)
Plummerella hantkeninoides Bronnimann, Maestrichtian (R)
Globotruncana citae Bolli, Campanian and Maestrichtian (S)
Globotruncana gansseri Bolli, lower Maestrichtian (R)
Age: Maestrichtian

These foraminiferal assemblages are identical to assemblages in unmetamorphosed rocks which occur along the southern boundary of the map area under the morros of San Juan (Pl. 1, B7; Pl. 2A, D3-4). Hence it is possible to elucidate contemporaneous events that took place within and without the mountain belt during the second metamorphic period. These events are described in a later section.

Rocks very similar to those described heretofore including the gray-green limestone were reported by Smith (1953, p. 54) in the vicinity of Cua (Hess, 1960, Fig. 2, H3). Farther eastward, R. La Forest showed the writer the same gray and green limestones exposed in road cuts 3.2 km south of the Santa Teresa road bridge (Hess, 1960, Fig. 2, I3). To the west the same rocks were observed about 1 km north of Los Naranjos (Hess, 1960, Fig. 2, D4). The limestone marker member of the Paracotos formation apparently crops out along the strike direction for more than 150 km.

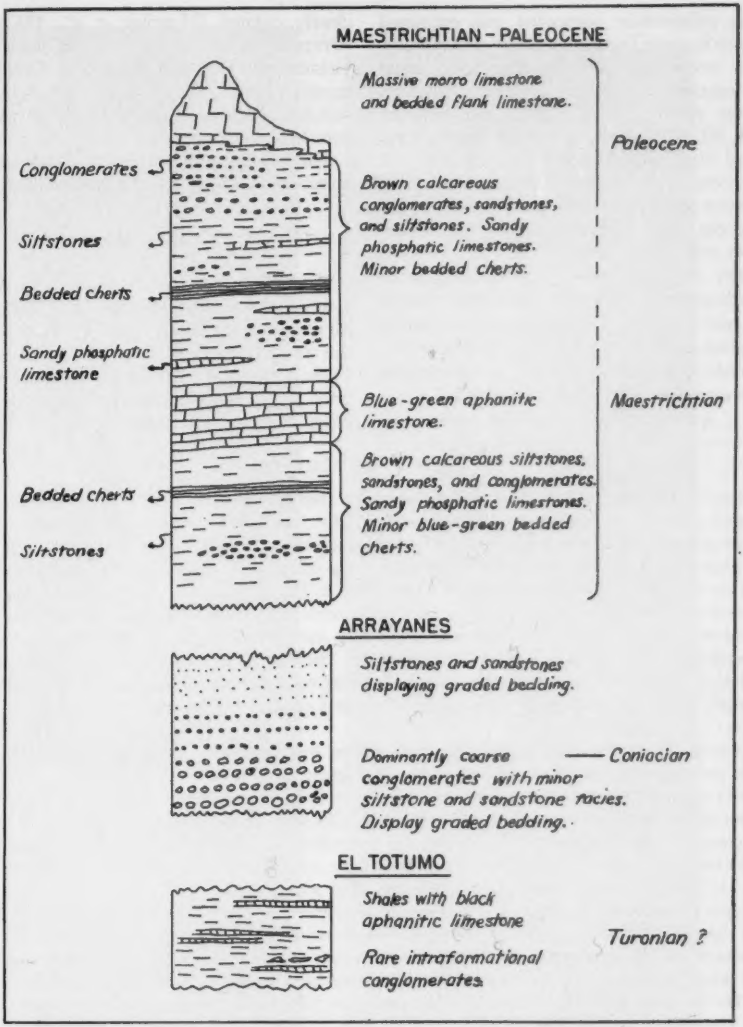


FIGURE 3.—STRATIGRAPHIC SUCCESSION OF THE SEDIMENTARY ROCKS
Shows Upper Cretaceous to Paleocene sedimentary rocks of the southern portion of the map area

UNMETAMORPHOSED ROCKS

Distribution and Stratigraphic Succession

Within the boundaries of the map area is a sequence of unmetamorphosed sedimentary rocks. These rocks are located mainly along the southern border in the area between San Juan de los Morros and San Sebastián. Several small outliers are known within the metamorphic zone. These include exposures at Villa de Cura (Pl. 1, G1-2), south of the Macuaya serpentine mass (Pl. 1, G4), east of the Hacienda El Carmen (Pl. 1, D7), and on the Santa Rosa road, 2 km west of the Hacienda Caicara (Pl. 1, K11). The last was mapped and described by MacLachlan (*in* MacLachlan, Shagam, and Hess, 1960).

The sedimentary succession was examined solely to increase knowledge of the metamorphic rocks. Accordingly only specific local areas were examined in detail. Two such localities are the morros of San Juan and environs (Pl. 1, B7; Pl. 2A), and Cerro los Burros 5 km west of San Sebastián (Pl. 1, B16; Pl. 2B).

Previous workers have assigned a variety of formation names to these rocks. However, the definitions are so uncertain that the writer prefers not to use them; on the other hand he has not the knowledge to define new ones. Accordingly no formation names are used in this report except for the name Arrayanes formation, applied to a sequence of lithic wacke siltstones, sandstones, and conglomerates which crops out east of San Juan de Los Morros (Pl. 1, A10-11). This name has never been clearly defined (Mencher *et al.*, 1953). The Arrayanes rocks form a mountain mass in the vicinity of San Juan known as Cerro Garrapata. This would perhaps furnish a more suitable name for the sequence if properly defined.

The stratigraphic succession of the unmetamorphosed rocks is summarized in Figure 3.

Arrayanes Formation

The Arrayanes formation is best exposed in a series of road cuts on the San Juan de Los Morros-San Sebastián highway beginning at the easterly police post outside San Juan. Characteristically the rocks are dark-bluish-gray lithic wacke siltstones, sandstones, and conglomerates. The siltstones break up into

PLATE 3.—PANORAMAS

FIGURE 1.—Panorama of the northern portion of the map area viewed from the east. Taken from the mountain crest west of the Hacienda Agua Fria (Pl. 1, L19). The lowest tree in the line of trees in extreme right foreground is located on the Agua Fria fault which marks the boundary between the Paracotos formation to the right (north) and the El Caño formation to the left (south). The hummocky patch immediately left of the bottom tree is the serpentinite of L18 in Plate 1. The trace of the Agua Fria fault is marked by the line of small saddles that trend away from the viewer toward center far background. The Río Pao crosses the field from right to left in middleground, hidden from view behind mountain masses in middleground. Highest point (center, horizon) is Pico Cataure, 1622 m. The Río Pao in this area is at an elevation of approximately 500 m. Note constancy of land forms irrespective of the nature of the underlying rock. Hill in immediate left foreground displays the typical characters of steep slope, grassy cover, absence of rock outcrop.

FIGURE 2.—Panorama of the morros of San Juan. Viewed from the east, from a point approximately 500 m west of the little morros in block 6E of Plate 2A. The highest morro center with tower atop appears in section F-G of Plate 2A. From the base of this morro to its crest is approximately 250 m. The large morro buttress, center right, is that of block 4C in Plate 2A. The steep grassy slope below the base of the left-hand group of morros is underlain by siltstones and limestones (Pl. 2A, section F-G). Small domical hill below the base of the morrow with tower is crowned by the unmetamorphosed aphanitic limestone at 4C in Plate 2A. The lower part of the same hill is composed of schists of the Santa Isabel formation. The two rock types are separated by a fault that dips steeply away from the viewer. The trace of the fault continues to the right (north) and curves behind the prominent pyramidal hill in center background. Left (south) of the domical hill the trace of the fault continues to the left margin of the field, hidden from view in the valley below the morros. The foreground and middleground are underlain by rocks of the Santa Isabel formation. The lower slopes of the gentle hill in right center are underlain by the metadiorite intrusion of block D5 of Plate 2A.

PLATE 4.—PHOTOMICROGRAPHS OF TUCUTUNEMO FORMATION ROCKS AND SANTA ISABEL FORMATION ROCKS

FIGURE 1.—Ar 616, polished specimen of limestone (×4), Tucutunemo formation. Plain light, showing clastic calcite grains. Note small calcite vein cutting clastic calcite grain; large vein has enveloped many of the calcite grains.

FIGURE 2.—Ar 809, limestone (× *ca* 25), Tucutunemo formation. Plain light, showing clastic calcite grain containing pattern of dots suggestive of algae.

FIGURE 3.—Ar 945, quartz-albite granulite (×10), Santa Isabel formation. Polarized light, showing albite porphyroblasts in a fine-grained granoblastic matrix of quartz and albite.

FIGURE 4.—Ar 953, quartz-albite granulite (× *ca* 66), Santa Isabel formation. Polarized light, showing albite porphyroblasts in fine-grained granoblastic matrix of quartz and albite.

FIGURE 1

FIGURE 2

PANORAMAS

FIGURE 1

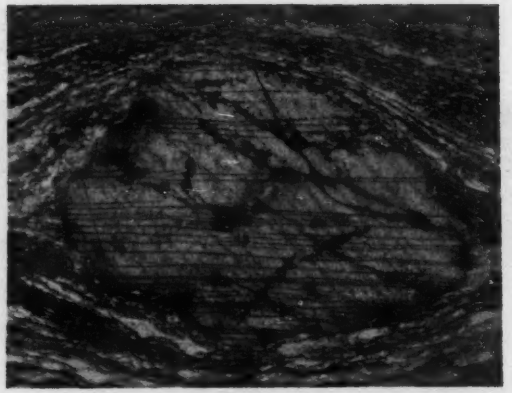


FIGURE 2

FIGURE 3

FIGURE 4

PHOTOMICROGRAPHS OF TUCUTUNEMO FORMATION ROCKS

FIGURE 3

FIGURE 4

PHOTOMICROGRAPHS OF TUCUTUNEMO FORMATION ROCKS

FIGURE 1

FIGURE 2

FIGURE 3

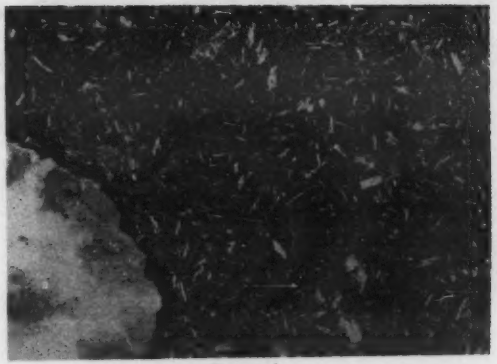


FIGURE 4

PHOTOMICROGRAPHS OF SANTA ISABEL FORMATION
ROCKS AND TIARA BASALT

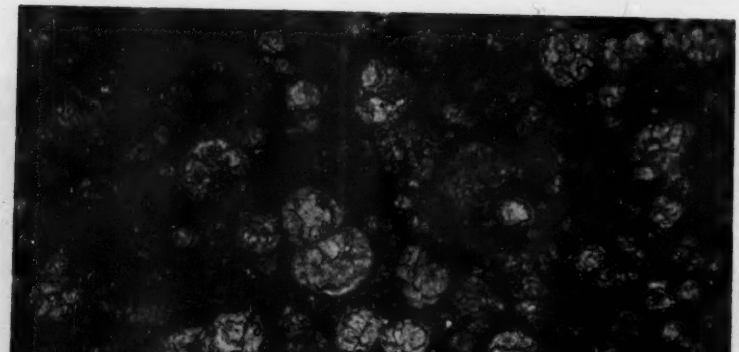


FIGURE 1

FIGURE 2

PHOTOMICROGRAPHS OF PARACOTOS FORMATION ROCK AND ARRAYANES FORMATION ROCK

razor-sharp sickle-shaped fragments in which the glint of detrital mica is ubiquitous. Approximately 2 km east of the police post a conglomerate facies consisting of cobbles up to fist-size becomes the dominant rock type. These exposures and some of the sandstone facies too display excellent graded bedding, but the finer fractions are poorly represented. If this primary structure is due to turbidity currents, possibly a rapid sequence of such mass movements would sweep away the fine material and continually add to the thickness of the coarse fraction.

Thin-section examination of conglomerates in which pebble sizes are in the range 2–10 mm revealed the following characters: The commonest constituents are basaltic lava pebbles (Pl. 6, fig. 2). In mineralogy and texture these are identical to the volcanic rocks of the Tiara formation. Also very common are fine-grained recrystallized chert pebbles which are similar to the metacherts of the El Chino and Santa Isabel formations. Pebbles of quartz-albite granulite and chlorite-quartz-albite schist were observed in moderate amount. These resemble the granulites and schists of the Santa Isabel formation. Also present are pebbles of dark-gray aphanitic limestone, the significance of which is discussed hereafter. Rarer pebble types included El Carmen-type basalt, a hornblende saussuritized plagioclase rock similar to some of the El Caño volcanic rocks, and a feldspathic sandstone of unknown provenance. Large single grains of quartz notable for their lack of strained extinction and free of bubble trains and inclusions are uncommon. The pebbles are well rounded and occur in a medium-grained matrix (30 per cent by volume) of the same constituents with much calcite. Calcite tongues from the matrix have partly replaced the pebbles. H. H. Hess pointed out to the writer that the heavy-mineral suite of the finer-grained facies is rich in chromite apparently derived from serpentine. Microfossils are conspicuously absent from the siltstones.

AGE AND CORRELATION: The nature of the lower and upper contacts of the formation is unknown. In the San Juan de los Morros area small patches of green rocks not unlike some of the rocks of the Villa de Cura group have been upfaulted along the contacts of the Arrayanes formation. Possibly this unit overlaps, with a marked angular unconformity, the Villa de Cura group. The upper contact of the Arrayanes formation is likewise uncertain. In the San Juan de los Morros area the contact with rocks of Maestrichtian and Paleocene age is poorly exposed.

Despite the evident lack of knowledge concerning this formation it constitutes a major time reference point in establishing the geologic history of the metamorphic rocks. In 1942, G. Pardo, while a student at the University of Caracas, found a Coniacian ammonite near San Juan de los Morros. The pertinent information concerning this find is as follows:

PLATE 5.—PHOTOMICROGRAPHS OF SANTA ISABEL FORMATION ROCKS AND TIARA BASALT

FIGURE 1.—Ar 463a, epidote-chlorite-quartz-albite schist (×10), Santa Isabel formation. Plain light, showing spherical epidote glomeroblasts. Large albite porphyroblast in bottom-left corner is partly replaced by chlorite and displays faint turbidity related to clouds of minute inclusions. Note association of epidote (light gray) and chlorite (medium gray) in top-left corner and in the glomeroblast at center bottom. Some replacement by calcite has been effected; *see* white area in left center. Note termination of chlorite flakes against the albite porphyroblast. Opaque mineral is pyrite, commonly enclosed by chlorite.

FIGURE 2.—Lower-left corner of Plate 5, figure 1 (× *ca* 35). Minute colorless rodlike mineral is actinolite.

FIGURE 3.—Ar 462a, chlorite-epidote-quartz-albite-glaucophane schist (× *ca* 66). Plain light. White patches consist of a granoblastic quartz-albite intergrowth. Light-gray mineral of high relief is epidote. Medium-gray flaky grains are chlorite. Dark-gray elongate prismatic grains are glaucophane. Note transition from chlorite to glaucophane in top- and bottom-right corners.

FIGURE 4.—Ar 411, basalt (×10), Tiara volcanic rocks. Plain light showing microlitic groundmass plagioclase, ubiquity of titanomagnetite microphenocrysts (minute black grains), calcite-filled vesicle.

PLATE 6.—PHOTOMICROGRAPHS OF PARACOTOS FORMATION ROCK AND ARRAYANES FORMATION ROCK

FIGURE 1.—Ar 627, limestone (×50), Paracotos formation. Showing abundance of Foraminifera. Dark-gray-black matrix areas consist of minute calcite grains.

FIGURE 2.—Mi 353, conglomerate (×15), Arrayanes formation. Plain light, showing dominance of Tiara basalt pebbles.

(1) The fossil was found in a road cut approximately 2 km east of the eastern police post outside San Juan de los Morros. In this locality the beds are vertical. The ammonite occurred in a thin siltstone zone overlain and underlain by coarse graded bedded conglomerates. If it were a reworked fossil it would have been deposited with the coarse fraction of the sequence. Apparently the shell was still gas-filled and hence deposited with the silty fraction. P. Leuzinger of the Mene Grande Oil Company has informed the writer that several more of these ammonites have been recovered from other localities and that none appeared to be reworked.

(2) The fossil is a near-perfect preservation of one side only. A. A. Olsson, who identified the specimen, wrote in a report to the Creole Petroleum Corporation.

"... It appears to belong with little doubt to the same species as an Ammonite common in certain limestone concretions near Ortiz [about 30 kms south of San Juan de los Morros]. . . . The fossil is near if not con-specific to *Peroniceras moureti* de Grossouvre from the Coniacian of France. . . ."

The Coniacian age of this bed in the Arrayanes formation establishes an upper age limit on the Villa de Cura group and the Tiara volcanism. These considerations are elaborated in the section on correlation.

H. H. Renz (1955) has renamed the Arrayanes section described as the Garrapata formation and combined the latter and the Maestrichtian Escorzonera formation into a lower and upper Arrayanes group. Renz informs the writer that he does not mean to imply thereby a continuous section from the Garrapata formation into the Escorzonera formation. The writer is unaware of any sedimentary succession known to bridge the gap between the two formations, and their interrelationships are not known. These ideas are diagrammed in Figure 7.

El Totumo Limestone-Shale Outcrops

In the description of the Arrayanes conglomerates reference was made to pebbles of a dark-gray aphanitic limestone. In the hand specimen the rock is dark gray to black and dominantly aphanitic, although reflections off cleavage faces of minute calcite grains are not uncommon. The rock breaks with a pronounced conchoidal fracture, and white calcite veins 1–5 mm thick are common. Thin sections viewed with the naked eye have a distinctive brownish cast. Under the microscope the rock is seen to consist of a fine-grained pseudo-isotropic matrix of calcite and carbonaceous material (?). Closely spaced anastomosing foliation planes outlined by carbonaceous material are common. Dispersed throughout the rock are undeformed microfossils constituting up to 15 per cent by volume of the rock, mainly Radiolaria and sponge spicules; rare Foraminifera are present.

These pebbles are significant because bedded limestones displaying the same megascopic and microscopic characters were observed near outcrops of the Arrayanes formation. The best exposures are located in a cut on the San Juan-San Sebastián road immediately south of the Arrayanes outcrops (Pl. 1, A12) and in a cut behind the homestead of the Hacienda El Totumo (Pl. 1, B13). The limestones form beds 5–30 cm thick and are intercalated in a sequence of fine brownish shales which are poorly consolidated. They are notably free of clastic sediment and originally were possibly of a calcareous ooze or mud in nature. In the field the remarkable similarity between the bedded limestone and the pebbles in the Arrayanes formation led to the suggestion that the El Totumo outcrops are pre-Arrayanes. H. M. Bolli of Trinidad Leaseholds, Ltd., kindly consented to examine specimens of the limestones. Excerpts from his report are as follows:

"... Globotruncanas are absent with the exception of one very doubtful double keeled form. Other planktonic genera are fairly common. Of the genus Gümbelina we found forms that are close to *G. pseudotessora* and *G. moremanni*. No specific determinations can be given for the Globigerinas and the Globigerinellas. The fauna, that has a somewhat dwarfed aspect, suggests a probable Turonian to Santonian age. . . . Maestrichtian may be excluded based on the absence of Pseudotextularias and distinct Rugoglobigerinas. . . ."

This report supports the contention that the El Totumo rocks are pre-Arrayanes but no older than Turonian.

Because the outcrops of these limestones and shales are poor and scattered, the writer is unable to describe a section or to define the upper and lower limits of the sequence. For this reason and also in view of the uncertain paleontological evidence there is no attempt here to define a new formation. The term El Totumo is used merely as a location name.

Renz and Leuzinger are not in agreement with the views stated herein. While admitting the strong resemblance between the limestone beds and the pebbles, they believe that their equivalence is not necessarily implied (Personal communication).

Maestrichtian-Paleocene Succession

Stratigraphically above the Arrayanes formation is a succession of siltstones, sandstones, conglomerates, and limestones of Maestrichtian to Paleocene age (Fig. 3). The relationship of these rocks to the Arrayanes formation is uncertain, as the contact zones are poorly exposed. Structural considerations and the occurrence of small serpentine bodies along the contacts suggest that the Arrayanes formation near San Juan de los Morros constitutes a block infaulted into the younger sedimentary sequence.

In the lower part of the succession is a prominent blue-green aphanitic limestone member. This rock was found below the morros of San Juan (D3, D4, Pl. 2A) and on the crest of Cerro los Burros (Pl. 2B). In thin section the limestone is identical to the Paracotos gray limestone. The dominant character is the rich assemblage of Foraminifera, now replaced by minute calcite rhombs, which occur in a very fine-grained calcite groundmass. Rounded quartz grains are present in accessory amounts only.

At the top of the sequence is the massive morro limestone which forms a series of prominent buttresses along the front of the metamorphic belt from San Juan de los Morros to San Sebastián and beyond (Pl. 3, fig. 2). The limestone is typically a gray, aphanitic, intensely brecciated rock with a marked conchoidal fracture. Staining with $Cu(NO_3)_2 \cdot 3H_2O$) (after Rodgers, 1940) failed to reveal the presence of dolomite. Nowhere did the writer observe bedding structures. Prominent widely spaced vertical and gently dipping joints give a blocky aspect to outcrops.

Below the blue-green aphanitic limestone member and above it to the uppermost morros limestone member is a succession of brown siltstones, sandstones, conglomerates, chert beds, and bedded limestones. Commonly these rocks contain rounded grains of plagioclase (5–30 per cent) and quartz (5–30 per cent) and rounded pebbles of finely crystalline chert (5–30 per cent), Tiara volcanic rocks (up to 20 per cent), and aphanitic limestone and other sedimentary rocks (up to 10 per cent). The remaining volume is made up of rounded irregular grains of collophane (as much as 20 per cent) and Foraminifera replaced by calcite, the whole in a fine-grained calcareous matrix (5–40 per cent by volume of total rock). In some rocks the proportion of collophane, Foraminifera, and calcite matrix considerably exceeds the detrital fraction. The suite of rocks ranges between calcareous feldspathic lithic wackes and sandy phosphatic foraminiferal limestone. The cherts are markedly laminated and many are a striking light blue.

AGE AND CORRELATION: Most of the sequence is highly fossiliferous, and definite Maestrichtian faunal assemblages are reported by Renz (1955) from several localities in the San Juan de los Morros-San Sebastián area. The writer submitted specimens of the blue-green aphanitic limestone from under the morros of San Juan and from the crest of Cerro los Burros to A. N. Dusenbury for paleontological analysis. Excerpts from his report are as follows:

Ar 948. Gray, slightly silty, argillaceous limestone, weathering to buff, cut by numerous veins of white calcite up to 10 mm in thickness. No trace of metamorphism. Foraminifera well preserved, not recrystallized, forming a very small percentage of the sample.

Foraminifera
Guembelina globulosa (Ehrenberg), Turonian to Maestrichtian (A)
Globigerina cretacea d'Orbigny, Cenomanian to Maestrichtian (A)
Rugoglobigerina macrocephala Bronnimann, Turonian to Maestrichtian (R)
Globigerinella messinae messinae Bronnimann, Maestrichtian (A)
Globotruncana lapparenti tricarinata (Quereau), Turonian to lower Maestrichtian (R)
Globotruncana gansseri Bolli, lower Maestrichtian (?)
Globotruncana spp. (R)
Age: Maestrichtian

L. B. 109. Gray, pyritic, foraminiferal limestone, weathering to buff due to alteration of the pyrite to limonite; cut by veins of white calcite up to 0.1 mm in thickness; often streaked with silt particles. No trace of metamorphism, Foraminifera fairly well preserved, occurring usually in layers, streaks or pockets.

Foraminifera
Robulus? sp. (R)
Guembelina globulosa (Ehrenberg), Turonian to Maestrichtian (A)
Guembelina plummerae Loetterle, Turonian to Maestrichtian (R)
Bulimina? sp. (R)
Neobulimina? sp. (R)
Gyroidinoides spp. (R)
Globigerina cretacea d'Orbigny, Cenomanian to Maestrichtian (A)
Globigerina spp. (F)
Globigerinella messinae messinae Bronnimann, Maestrichtian (F)
Globotruncana citae Bolli, Campanian and Maestrichtian (R)
Globotruncana gansseri Bolli, lower Maestrichtian (S)
Globotruncana lapparenti Brotzen, Turonian to Campanian (R)
Age: Maestrichtian

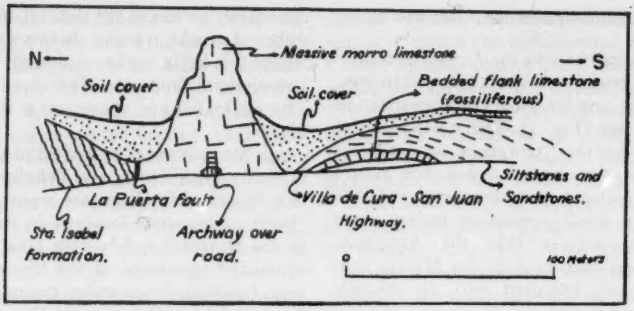


FIGURE 4.—ROCKS EXPOSED IN A ROAD CUT AT LA PUERTA (Pl. 1, B9; Pl. 2A, B7)

L. B. 110. Gray, slightly silty limestone, weathering to buff; cut by veins of white calcite up to 2 mm in thickness. No trace of metamorphism. Foraminifera well preserved, usually few and scattered but occasionally concentrated in layers or streaks.

Foraminifera
Dentalina sp. (R)
Guembelina globulosa (Ehrenberg), Turonian to Maestrichtian (A)
Guembelina plummerae Loetterle, Turonian to Maestrichtian (S)
Gyroidinoides sp. (R)
Globigerina cretacea d'Orbigny, Cenomanian to Maestrichtian (A)
Globigerina spp. (F)
Globigerinella messinae messinae Bronnimann, Maestrichtian (A)
Plummerella hantkeninoides Bronnimann, Maestrichtian (R)
Globotruncana gansseri Bolli, lower Maestrichtian (R)
Globotruncana? sp. (R)
Age: Maestrichtian

These assemblages and those found in the Paracotos gray limestone are similar.

Renz examined specimens of the limestone from the outcrops south of Villa de Cura. He felt that an upper Cretaceous age was suggested, but that there were ". . . certain faunistic elements (algae, etc.) which seem to be similar or the same as in the Paleocene" (*quoted from* J. C. MacLachlan, 1952, Ph.D. Thesis, Princeton Univ., p. 57).

Paleocene faunas are known from several localities, too. These include faunas from bedded limestones and siltstones on the east side of the San Juan morros below the Morro del Faro (morro with tower; *see* section F–G, Pl. 2A); faunas from similar (possibly the same) rocks in road cuts 50 m south of the arch at La Puerta (Fig. 4; Pl. 2A, B7); faunas from siltstones on the front lower slopes of Cerro los Burros (Pl. 2B); from a gray aphanitic limestone member in the outcrops on the Santa Rosa road described by MacLachlan, Shagam, and Hess (1960) (Pl. 1, K11). A Paleocene fauna was also obtained from the vertical wall near the top of the Morro del Faro (Renz, 1955). So far as the writer is aware this is the only reported instance of a diagnostic fauna found in the morro limestones of the San Juan de los Morros-San Sebastián area.

The natures of the formation boundaries in the Maestrichtian-Paleocene succession described are only imperfectly known. Sedimentary rocks of Maestrichtian age rest with marked angular unconformity on the Villa de Cura group. This was observed on the northern flank of the morros of San Juan. On Cerro Escorzonera, about 3 km northwest of San Sebastián (Pl. 1, D-C18), the Maestrichtian overlaps disconformably onto the Tiara lavas. It is likely that this relationship also obtains on the south side of the morros of San Juan (Pl. 2A, D3), but the actual Tiara-Maestrichtian contact here is not exposed.

The Maestrichtian-Paleocene boundary is paleontologic, not lithologic. In the San Juan de Los Morros area there appears to be a conformable sequence from Maestrichtian rocks up into the Paleocene morro limestone (*see* map and sections, Pl. 2A), although Renz (1955) writes:

"The Escorzonera [= writer's Maestrichtian] formation can be followed from Cerro Escorzonera to the southwest, over a distance of about 7 kilometers. It occurs again in the San Juan de los Morros area, unconformably underlying the Guarico [= writer's Paleocene] formation, east and west of the large morros."

Elsewhere there appears to be a break in the succession. This is evident in the Cerro los

Burros area (*see* map and sections, Pl. 2B) and in the Santa Rosa road exposures described in MacLachlan, Shagam, and Hess (1960), where Paleocene rocks rest with angular unconformity on the Maestrichtian Paracotos formation. It is not known whether or not this discontinuity coincides with the change in fauna from Maestrichtian to Paleocene rocks. In places the Paleocene overlaps directly onto the Villa de Cura group or onto the Tiara lavas (Pl. 2A, C3, C6).

DEPOSITIONAL ENVIRONMENT: The calcareous nature of the Maestrichtian-Paleocene rocks and the dominance of detrital volcanic and metamorphic material suggest a transgression by a shallow arm of the sea, with the metamorphic and volcanic rock belt as a detrital provenance to the north. During the early stages of this transgression the shore line was at least as far north as the Santa Rosa road and possibly reached to near Cagua (Hess, 1960, Fig. 2, F3). In this broad shallow sea the early Maestrichtian sediments (including what is now referred to as the Paracotos formation in the north) were deposited. This early transgression was followed by a deformation during which the Maestrichtian rocks in the southern part of the map area were merely carried forward on the south flank of the deforming structure and remained unaffected, whereas the Paracotos section was caught up within the deforming structure and suffered mild dynamometamorphism. Later, in latest Cretaceous or Paleocene time, a weaker transgression led to the deposition of the sedimentary rocks at Villa de Cura and along the Santa Rosa road area. In the southern area deposition was possibly continuous. During this episode the morro limestone was deposited. Further deforming movements in Late or post-Paleocene time resulted in the folding of the Paleocene beds (Fig. 5).

The morro limestone of the San Juan area has been interpreted as vertically bedded limestone by Caudri (1944) and as large slump blocks by Kugler (1953). The Paleocene fauna described by Renz indicates, however, that these rocks follow in normal succession on earlier gently dipping siltstones (*see* sections, Pl. 2A). The writer considers the morros to be reef-type limestones. Löwenstam (1950 p. 430) has defined reefs in terms of the biologic potentials to

"... erect rigid topographic structures by frame building, sediment-retention and binding, and to create a wave resistant structure".

Information is insufficient for evaluation of the morro limestone in these terms. The enormous thickness (in the Morro del Faro exceeding 250 m) of brecciated rock containing fragments of organic remains is typical of diagenetically altered reefs and suggests the presence of organisms capable of binding organic debris into a rigid structure. Whether or not such a structure was wave resistant is not known.

Under the reef hypothesis the fossiliferous bedded limestones at the base of the San Juan morros (Pl. 2A, section F-G) and on the south side of the La Puerta morros (Fig. 4) are considered to be the flank beds derived in part from the detritus of the morro (= reef) facies. The bedded limestones in the Villa de Cura and Santa Rosa road exposures are considered to be equivalent in age and type to these bedded limestones. The conspicuous relationship between the morros and the metamorphic front indicates that the present mountain front here was a Paleocene shore line with fringing reefs and with the open sea to the south. Embayments of this sea extended far back into the mountains to the north. The present longitudinal valley from Villa de Cura to Santa Rosa was occupied by an arm of this Paleocene sea.

Igneous Rocks

A vertical sheet of andesite about 2 m thick conformably intrudes conglomerates of the Arrayanes formation in a cut on the old San Juan de los Morros-San Sebastián road, about 5 km east of San Juan. This constitutes the sole evidence observed by the writer of volcanism of post-Tiara age.

On the same road in a cut approximately 1.5 km east of San Juan there are outcrops displaying marked spheroidal weathering and volcanic aspect. Thin sections show the rock is markedly brecciated. The dominant constituents are green amphibole, sodic plagioclase, and chlorite. The rock has the texture of an amphibolitic schist. Some patches consist of equigranular interlocking tablets of plagioclase with anhedral grains of green amphibole in the interstices. These rocks may represent large detrital blocks of Santa Isabel schist within the Arrayanes formation or possibly upfaulted blocks of the same formation. Their peculiar mineralogy precludes their being unmetamorphosed volcanic rocks.

Approximately 800 m east of the last-named outcrop, a road cut displays vertical beds of the Arrayanes formation overlying a coarse-

FIGURE 5.—DIAGRAMMATIC NORTH-SOUTH SECTION ACROSS MAP AREA SHOWING DEPOSITION AND DEFORMATION IN MAESTRICHTIAN TO PALEOCENE TIME

grained igneous rock. This appears to intrude the Arrayanes formation, but the relationship is not explicit. In thin section the rock is seen to be a normal gabbro consisting of interlocking subhedral grains of saussuritized plagioclase and clinopyroxene. The clinopyroxene grains have exsolution lamellae along (100) and (001) partings. Widespread replacement by prehnite was observed in one specimen. The gabbro has undergone minor brecciation but is otherwise unmetamorphosed. It could conceivably be related to the Tiara volcanism.

Structural Geology

The major portion of the map area is occupied by the rocks of the Villa de Cura group; the rocks trend approximately N. 75° E. and dip southward. Many of the dip angles registered on the map are uncertain because of drag folding. A large number of observations indicates that the Villa de Cura group dips rather uniformly southward at an angle of about 25°.

In the northwest portion of the map area the Tucutunemo formation consists of an elongate open basin with vertical axial plane trending approximately N. 70° E.

Between the Tucutunemo basin and the uniformly southward-dipping formations of the Villa de Cura group, there is a structural graben now occupied by the Paracotos formation. The graben is bounded on the north and south by the Santa Rosa and Agua Fria faults respectively and is marked by a line of serpentine intrusions for a portion of its length. T. A. Konigsmark (1958, Ph.D. thesis, Princeton Univ.) has traced this tectonic feature westward to a point north of Belén (Hess, 1960, Fig. 2, E4), and the writer has observed the south margin of it eastward as far as Santa Teresa (Hess, 1960, Fig. 2, I3). The graben is therefore known over a strike length of at least 110 km. It ranges in width from 1 to 5 km.

Another structural unit comprises a block of unmetamorphosed sedimentary rocks downfaulted against the Villa de Cura group, along the southern margin of the map area. This area consists of a sequence of small anticlines and synclines which range from open structures to tight folds which are generally asymmetrically overturned toward the north. These folds strike parallel or subparallel to the structures of the metamorphic rocks.

Lesser structural features are as follows:

FAULTS: The most prominent faults strike parallel to the regional trend of formations. The Santa Rosa and Agua Fria fractures that bound the Paracotos graben were probably normal faults that were rotated somewhat during the later deformations. For this reason the Agua Fria fault at first appears to be a high-angle reverse fault. The strongly sheared rocks in the vicinity of the Santa Rosa fault suggest that some strike-slip movement (right lateral) also occurred along that fracture. Possibly a major strike-slip fault occurs along the front of the metamorphic ranges, but a covering of younger rocks has obscured the relationships. The La Puerta fault that marks the metamorphic front at present is a normal fault of minor displacement. Paralleling the normal faults and the regional strike direction are numerous small-scale thrust faults and high-angle reverse faults. One thrust fault cutting Paleocene rocks is clearly exposed in a road cut at the northeastern entrance to San Juan de los Morros (Pl. 2, E8).

Striking across the regional trend of formations and grouping about the northwest and north-northeast directions are graben-and-horst structures, whose constituent faults are of the normal variety, and single near-vertical normal faults. The Guarico fault trends west-northwest and is a strike-slip fault displaying right-lateral movement.

Most faults are of minor displacement. The Santa Rosa and Agua Fria faults have throws of not less than 500 m. Assuming no vertical movement, the horizontal movement along the Guarico fault has been in excess of 3 km.

The Guarico fault has been offset by the Paracotos graben near Villa de Cura and has not displaced the metamorphic boundary in the La Puerta area (Pl. 1, B9) and is accordingly considered to be one of the oldest in the map area. All other faults cut Maestrichtian or younger rocks, but it is likely that many of these were originally formed during or soon after the main Middle Cretaceous deformation and then were reactivated in succeeding deformations.

FOLDS: Small open folds of amplitudes up to 5 m are common to all formations within the map area. Drag folding is limited to the metamorphic zone and was observed in single hand specimens and up to amplitudes of 3 m. These small-scale folds generally strike parallel to the regional trend of formations and plunge gently east and west. In the highly incompetent phyllites of the Tucutunemo and Paracotos formations they are of variable trend and plunge.

FOLIATION: The dominant planar features parallel primary bedding planes. This is readily determined by the correlation of foliation with

bedding at sharp lithologic discontinuities and where such features as graded bedding are present. In some rocks of the Villa de Cura group only, this foliation is a schistosity.

Less well developed is fracture cleavage parallel to the axial planes of tight folds within the phyllites of the Tucutunemo and Paracotos formations and within the chlorite schists of the Villa de Cura group.

LINEATION: Linear features commonly parallel the regional strike. Best developed are microcorrugations in the phyllites of the Tucutunemo formation and in the more chlorite-rich rocks of the Villa de Cura group. These are rare in the Paracotos phyllitic shales and where present are weakly developed.

Lineation related to alignment of mineral grains is seldom strongly developed. In some outcrops the pyroxene phenocrysts of the El Carmen lavas are flattened and stretched-out in the direction of strike. Rods, needles, and prismatic grains of actinolite and glaucophane in the Santa Isabel rocks generally display a weak to moderate alignment parallel to the strike, too. The same type of lineation is displayed by quartz grains in the sandstones of the Tucutunemo formation. Large clastic calcite grains in the limestones associated with the Tucutunemo sandstones display the same character. Uncommonly this strike lineation is also displayed by the pebbles of the gray-green conglomerate of the Paracotos sequence. An apparent pronounced stretching-out of the pebbles in the strike direction is actually no more than the normal "soling" of stream-worn pebbles. In thin section, however, the molding of pebbles on their neighbors indicates that a moderate amount of this stretching-out has taken place.

The linear features are generally only moderately developed, but in some outcrops they are very pronounced. In some outcrops a strong down-dip lineation of the same elements which constitute the strike lineations is developed (*e. g.*, the volcanic pebble beds in the Santa Isabel formation exposed in a road cut about 2 km northwest of La Puerta, (Pl. 2A, A5). Here again the stretching-out of the pebbles is more apparent than real. Such down-dip lineations are considered to be related to the close proximity of such compressional features as high-angle reverse faults. D. B. MacKenzie (1953, unpub. Ph.D. thesis, Princeton Univ.) has described similar down-dip lineations in the vicinity of thrust faults and quotes many other instances from the literature.

TECTONIC INTERPRETATION: The structural relationships within the Central Aragua area cannot be considered as the product of a single tectonic episode. The deformations in other areas of the greater Caribbean island-arc system must necessarily have exerted complementary stresses in this area. Furthermore, as the main deformations may not have been contemporaneous in all parts of the arc, it is likely that stresses of variable direction and intensity were exerted over a long period of time. Accordingly the structural interpretation given hereafter is necessarily an oversimplification.

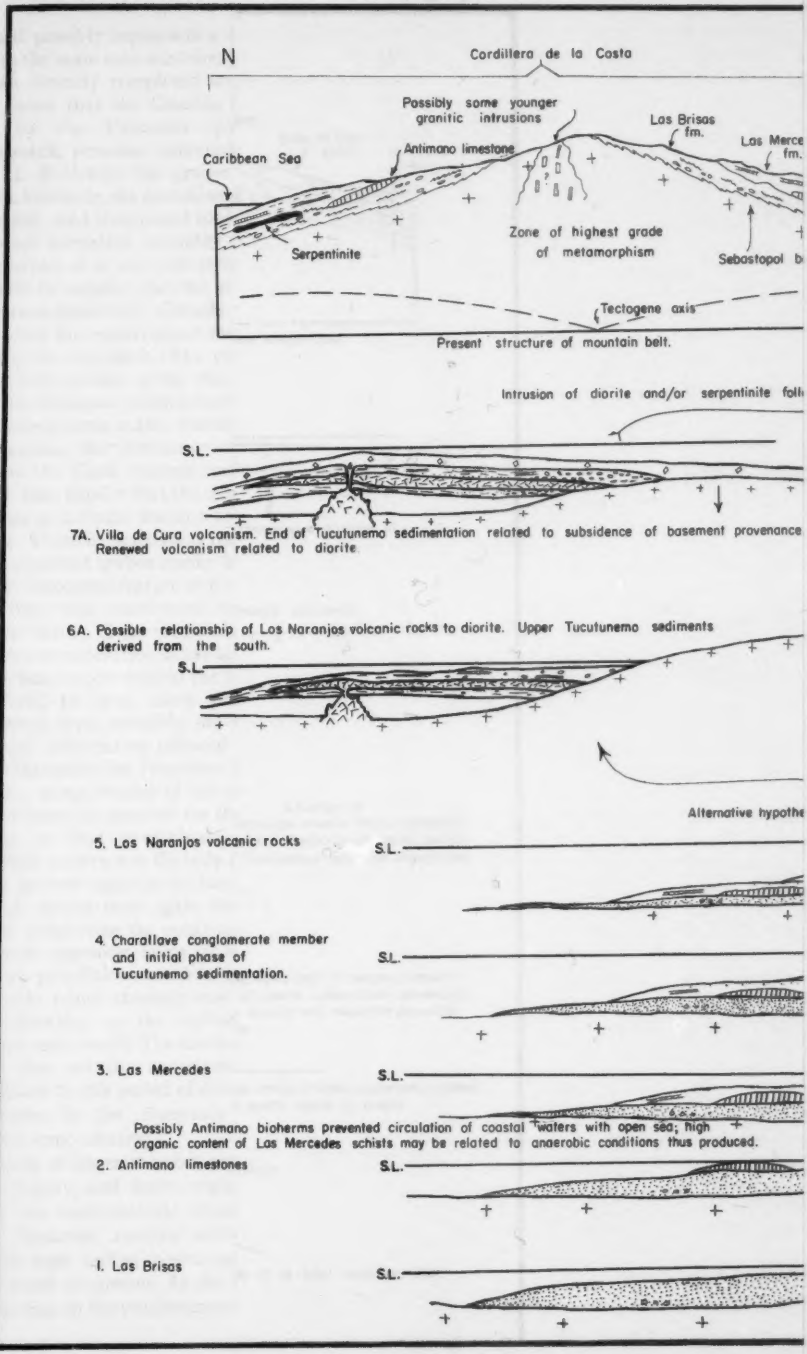
The dominant structural features which trend N. 75° E. were developed as a consequence of the first period of deformation in Middle Cretaceous (?) time. Such features are presumably related to compressional stress directed north-northwest–south-southeast. The elongation strain developed in the direction normal to this would produce the normal faults which group about the northwest and north-northeast directions.

These stresses could not produce the strike-slip movement that took place along the Guarico or Santa Rosa faults. In an attempt to explain similar features in the Caracas region, Dengo (1953) proposed that such strike-slip movement was produced by a shear couple acting in an east-west direction and with right-lateral movement. Dengo suggested that a component of this couple would produce the compression in the north-northwest–south-southeast direction.

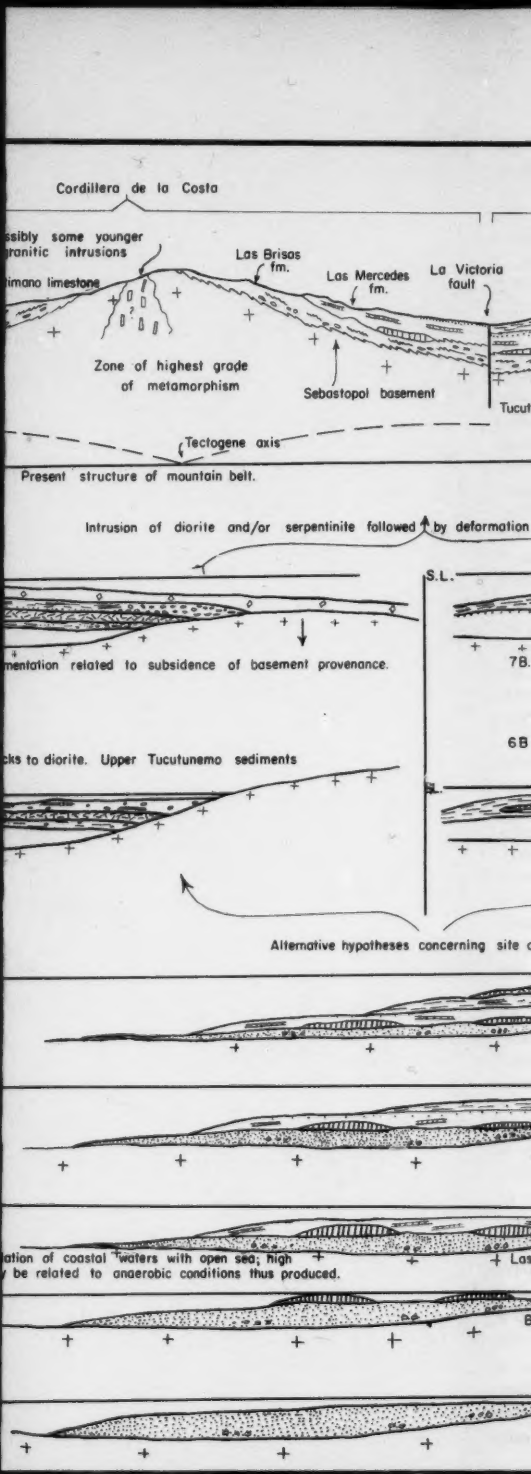
Dengo's observations are supported by Rod (1956), who compiled the records of major strike-slip faults throughout northern Venezuela and showed that such faults with right-lateral movement are a common and prominent tectonic feature in this part of the Caribbean area. Evidently the east-west shear couple proposed by Dengo is of regional significance.

Hess and Maxwell (1953) and Christman (1953) have implied a movement of the crustal block under the Caribbean sea eastward toward the Lesser Antilles. The shearing stresses proposed by Dengo could have been produced as a result of this movement. A similar explanation has been advanced by Vening Meinesz (1954) to account for prominent shearing phenomena in Sumatra. He has suggested that crustal blocks on the concave (northwestern) side of the Indonesian arc have moved relatively southeastward.

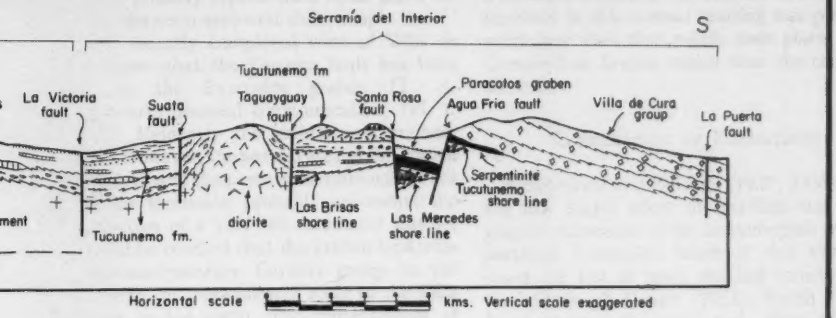
The Guarico strike-slip fault was probably developed during the first period of deforma-


N
Cordillera de la Costa
Possibly some younger granitic intrusions
Las Brisas fm.
Las Merce fm.
Caribbean Sea
Antimano limestone
Serpentinite
Zone of highest grade of metamorphism
Sebastopol b
Tectogene axis
Present structure of mountain belt.
Intrusion of diorite and/or serpentinite foli
S.L.
7A. Villa de Cura volcanism. End of Tucutunemo sedimentation related to subsidence of basement provenance. Renewed volcanism related to diorite.
6A. Possible relationship of Los Naranjos volcanic rocks to diorite. Upper Tucutunemo sediments derived from the south.
S.L.
Alternative hypothe
5. Los Naranjos volcanic rocks
S.L.
4. Charallave conglomerate member and initial phase of Tucutunemo sedimentation.
S.L.
3. Las Mercedes
S.L.
Possibly Antimano bioherms prevented circulation of coastal waters with open sea; high organic content of Las Mercedes schists may be related to anaerobic conditions thus produced.
2. Antimano limestones
S.L.
1. Las Brisas
S.L.

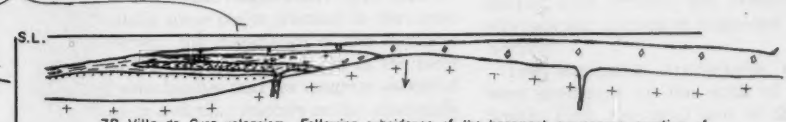
DIAGRAMMATIC PRESENTATION OF GEOLOG



NTATION OF GEOLOGIC HIST



d by deformation and regional metamorphism.



7B. Villa de Cura volcanism. Following subsidence of the basement provenance eruption of Villa de Cura volcanic rocks takes place towards the south.

6B Tucutunemo sedimentation continues after the end of Los Naranjos volcanism.

concerning site of volcanism.

Eruption of Los Naranjos volcanic rocks represents first positive product of orogeny. Comparatively brief period of eruption explains paucity of Tucutunemo sediment interbedded with the volcanic rocks.

Sharp uplift of provenance (possibly signifying start of orogeny) results in deposition of Charallave conglomerate. Removal of quartz rubble from provenance once again exposes granitic basement rocks to erosion and results in deposition of feldspathic sediments during Tucutunemo time.

Transgressing epicontinental sea. Minor volume of clastic sediments suggests low-lying terrane to south. Accumulation of quartz rubble on deeply weathered provenance.

Las Brisas shore line

Provenance much reduced in relief

Biohermal growth (limestones.)

Arkoses and feldspathic sandstones suggest provenance of at least moderate relief and deposition in shallow waters near shore.

C HISTORY UP TO THE FIRST DEFORMATION

tion and possibly represents a shear plane related to the main east-west shear couple.

Work recently completed west of Villa de Cura shows that the Guarico fault has been offset by the Paracotos graben (T. A. Konigsmark, personal communication) (Pl. 1, G-H, 1). Evidently the graben is a younger feature. However, the general area of the graben is complex , and the present containment of the Paracotos formation probably represents the rejuvenation of a very old structural feature. It should be recalled that the graben separates the metasedimentary Caracas group to the north from the metavolcanic rocks of the Villa de Cura to the south. The concentration of serpentinite masses along this zone suggests that the ultramafic magma may have been injected along some major fracture in this area. Furthermore, the dominance of the intrusive facies of the Tiara volcanic rocks in the same general zone implies that the magmas ascended the same or a similar fracture as the ultramafic magma. There is hence good reason to suspect that the present graben marks the location of a primary structural feature of first-order magnitude that was reactivated throughout the geologic history of the mountain belt.

From a consideration of the age of formations (*see* section on correlation) the main orogeny is considered to have taken place in Middle Cretaceous time, certainly pre-Turonian time. A second deformation followed the deposition of the Maestrichtian Paracotos formation. The direction of application of the stresses appears to have been the same as for the earlier deformation, so that re-emphasis of the earlier structural pattern was the only result.

The graben appears to have existed as a physical trench once again during Paleocene time to judge from the occurrence of scattered Paleocene exposures along its length. A third Late or post-Paleocene deformation of comparatively minor strength was applied in the same direction as the earlier deformations with the same result. The south-dipping reverse faults that cut the unmetamorphosed rocks are related to this period of deformation. Older structures in the mountain belt possibly suffered some rotation.

Periods of isostatic uplift probably followed each orogeny, and faults originally developed under the compressional stresses of orogeny later displayed relative movement of the normal type during postorogenic periods of adjustment to stresses. As the area under discussion was on the southernmost margin of the belt of deformation, the amount of movement involved in this normal faulting was probably much less than that which took place in the Caracas-Los Teques region near the center of the belt.

Correlation of Formations

Aguerrevere and Zuloaga (1937; 1938) made the first major effort to establish the stratigraphic succession of the metamorphic rocks of northern Venezuela. Much of this work has stood the test of more detailed scrutiny, but the efforts of Dengo (1953), Smith (1953), MacLachlan, Shagam, and Hess (1960), MacKenzie (1960), and the writer have necessitated some revision and refinement of the stratigraphic succession suggested by the first workers.

Two important stratigraphic relationships were confirmed by the work of Dengo and Smith. First, the basal unit of the metamorphic rocks, the Las Brisas formation, unconformably overlies the granitic Sebastopol basement complex. The unconformity is established by Basic dikes which cut the gneiss but terminate against the Las Brisas rocks and also by Sebastopol pebbles in the basal conglomerate of the overlying formation. Second, the Las Brisas formation is followed conformably by the Antimano metalimestone formation and the calcareous graphitic schists of the Las Mercedes formation. Dengo considered that the last-named was followed conformably by the fine-grained green metatuffs of the Tacagua formation which crops out in the Río Tacagua below the Caracas-La Guaira road. These formations constitute the Caracas group as defined by Smith and Dengo.

Smith considered the formations of the Caracas group to have been deposited on a stable shelf in a shallow transgressing Early Cretaceous sea (Pl. 7). Las Brisas sedimentation began with an early arkosic phase which now exists as conglomeratic gneiss or schist. The local distribution of the conglomeratic layers suggests that there were small islands of basement rocks in the epicontinental sea. This phase was followed by a calcareous sandstone facies (now dolomitic microcline gneisses) with more conglomeratic zones that suggest shallow-water, near-shore conditions. The amount of coarse detritus and the presence of feldspar point to a hinterland provenance of at least moderate relief. The succeeding sericitic schists of the upper Las Brisas indicate a period of dep-

osition of shales that was related either to more distant shore line or to a considerable reduction in the relief of the provenance area to the south.

The Las Brisas sequence and nature of sedimentation indicates offshore deposition under quiet conditions. In many cases the arenaceous rocks are poorly sorted; the strong, uniform, even bedding which is characteristic of shallow-water shelf deposits is not common in the Las Brisas formation. There has been little if any winnowing of the sediments. This suggests deposition in water of a depth sufficient to be below wave action.

The Antimano limestones are probably of biohermal origin, formed in shallow waters and at a time when the hinterland had been so reduced or submerged that clastic sedimentation was effectively eliminated.

The Las Mercedes formation appears to extend farther south than the Las Brisas sequence. Apparently the shallow epicontinental sea continued to transgress during Caracas time. The Las Brisas shore line was possibly along the Güigüe-Paracotos line (Hess, 1960, Fig. 2, D3–H2); that of Las Mercedes time was possibly 10–15 km farther south, passing approximately through Villa de Cura. The shales (now calcareous graphitic schists) and thin-bedded limestones of the Las Mercedes formation are devoid of coarse clastic material, and deeper-water conditions or a very low-lying terrane to the south are implied. The high organic content of the schists suggests a barrier to the north (possibly the Antimano bioherms) resulting in anaerobic conditions in the basin of deposition.

The final stage of Las Mercedes sedimentation, the deposition of the Charallave conglomerate member, represents the sudden reappearance of coarse clastic detritus. Both pebbles and matrix consist only of quartz, suggesting that a quartzose rubble accumulated on the surface of a deeply weathered low-lying provenance. Smith suggests that a slight uplift served to sweep the residual quartz into its basin of deposition and that the uplift into the south marked the beginning of orogenic activity. The widespread distribution of the conglomerate indicates that the deposition cannot be ascribed to a local circumstance.

The conglomerates of the Caracas group thicken toward the south, and pebble sizes increase in the same direction, indicating the source area of the Caracas group lay to the south. The total thickness of the deposits is approximately 3000 m, although thicknesses in such deformed metamorphic rocks are difficult to estimate.

Following the work of Dengo and Smith, J. C. MacLachlan traced the Caracas group westward to the region immediately north of Villa de Cura. Within the area mapped by the writer, the Las Brisas, Antimano, and Las Mercedes formations do not occur. The available information suggests that the Tucutunemo formation conformably overlies the Las Mercedes formation and should be included as the uppermost member of the Caracas group. This is based on the following evidence:

(1) The Tucutunemo formation has lithologic similarities to the Las Brisas formation. The dominance of quartz, feldspar, and quartz-plagioclase (granitic ?) grains and pebbles, and the complete absence of mafic volcanic debris and pebbles are characteristic of the conglomerates of all these formations. The limestones, likewise, are similar. Reference has been made previously to the fact that some of the quartz pebbles of the Tucutunemo rocks have the same black color so strikingly developed in the Charallave conglomerate member of the Las Mercedes formation. Despite the fundamental similarity in lithology, certain differences in the nature and succession of the rocks make it unlikely that the Tucutunemo formation is a facies of the Las Brisas or Las Mercedes formations.

(2) The Tucutunemo and Las Mercedes formations appear to be structurally conformable in the Central Aragua region. A small outlier of Tucutunemo rocks appears to follow conformably on definite Las Mercedes schist 2 km north-northwest of Villa de Cura (MacLachlan, Shagam, and Hess, 1960) (Pl. 1, I1). East of this outcrop, northeast of the Hacienda La Lagunita (Pl. 1, J-K 4), the Tucutunemo rocks again appear to rest conformably on Las Mercedes schists, although unequivocal evidence is lacking because of poor outcrop.

(3) The Tucutunemo formation has attained a grade of metamorphism that is greater than that of the Tiara volcanic rocks and Paracotos formation but approximately the same as that of the Las Mercedes formation in the Aragua area. These views have been confirmed by T. A. Konigsmark (1958, Ph.D. thesis, Princeton Univ.), who recently traced the Tucutunemo formation westward and found that it conformably overlies the Charallave conglomerate in the area of Belén, south of Lake Valencia (Hess, 1960, Fig. 2, E4). For these reasons it is

here included as the uppermost formation of the Caracas group.

MacLachlan, Shagam, and Hess (1960) described the Los Naranjos volcanic rocks and showed that they are interbedded in the Tucutunemo metasedimentary rocks. The metasedimentary and metavolcanic rocks of the Tucutunemo formation lie along strike from lithologically similar rocks assigned by Smith to the lower and middle Paracotos formation and are hence considered to be equivalent. Within the Tucutunemo formation, the Los Naranjos volcanic member and the equivalent rocks in Smith's lower and middle Paracotos formation include light-green laminated aphanitic tuffs. These rocks resemble the metatuffs in Dengo's Tacagua formation, and in all three areas they appear in approximately the same stratigraphic position relative to the Las Mercedes formation. Accordingly they are correlated as being roughly equivalent. Smith included some Los Naranjos volcanic rocks with his Tiara formation, but the two volcanic sequences are distinct petrologically, display different grades of metamorphism, and are certainly of different ages. As defined in this report the Tiara volcanic rocks definitely postdate the main period of deformation and are hence younger than the Tucutunemo formation (= Smith's lower and middle Paracotos). On the other hand the Tiara volcanic rocks are older than the Paracotos formation (= Smith's upper Paracotos).

The nature of the Tucutunemo metasedimentary rocks suggests that the removal of the Charallave quartz pebbles from their provenance as a result of uplift in that region must have exposed once again granitic basement rocks to erosion. Consequently the sediments deposited after the Charallave conglomerate were not unlike those laid down during the deposition of the Las Brisas formation. In this instance, however, the environment of deposition was related to tectonic factors. The lower Tucutunemo rocks consist of carbonaceous and chloritic phyllites interbedded with feldspathic quartz conglomerates. Shaly sedimentation in water of at least moderate depth alternated with apparent inshore deposition of conglomerate, implied by the poor sorting and angularity of the sediments.

This period of deposition was followed by the eruption of Los Naranjos lavas and tuffs. MacLachlan, Shagam, and Hess (1960) observed that the lavas and tuffs are interbedded with fine graphitic schists poor in clastic material. In two places only, thin beds of feldspathic quartz conglomerates were observed interbedded with the lavas. Probably the lava flows were subaqueous and in water of at least moderate depth.

MacLachlan, Shagam, and Hess showed that the feldspathic quartz conglomerates and grits of the upper Tucutunemo section overlie conformably the Los Naranjos volcanic rocks. The fact that nonvolcanic sedimentation during Los Naranjos time is almost entirely represented by graphitic phyllites and schists, whereas postvolcanic sedimentation consisted dominantly of arenaceous and rudaceous rocks, suggests that the termination of volcanism and the appearance of the grits and conglomerates may have been tectonically controlled. The poor sorting of the upper Tucutunemo rocks, the abundance of feldspathic detritus, and the angularity of grains in the sandy facies suggest that the original sediment was derived from a provenance of at least moderate relief and was rapidly swept into the basin of deposition. These petrologic and textural characters suggest a faulted shore-line with moderately deep water close inshore. Between floods of coarse clastic sedimentation there were infrequent quiet periods during which limestones were precipitated. In some cases calcite grains were gently rolled and sorted on the accumulating lime mud. Not infrequently detrital material reached areas of lime-mud deposition, and arenaceous limestones resulted.

The Tucutunemo conglomerates thicken and pebble sizes increase toward the south. The geographic location of the Tucutunemo shoreline is not known. The size of the pebbles and the existence of arkosic beds mistaken for granitic sills in the field both imply that the shore line in Tucutunemo time was not far south of the present area of outcrop of the formation.

The exact position of the Caracas group on the geologic time scale is unknown. Dengo and Smith have reviewed the available information. Poorly preserved fossil remnants in the Zenda limestone phase of the Las Brisas formation and the Los Colorados member of the Las Mercedes formation suggest an Early Cretaceous age. This is supported by the lithologic similarities between the Caracas group and unmetamorphosed formations of Early Cretaceous age in eastern and western Venezuela. The ages and correlations suggested are shown in the lower part of Figure 7.

The relative age of the Villa de Cura group remains to be discussed. The grade of metamorphism attained by the rocks of this group indicates that they too, were deposited before the main metamorphic episode. No contact between these rocks and those of the Caracas group or Sebastopol basement complex was observed in the Central Aragua area, hence their relative position in the stratigraphic column is uncertain. The volcanic rocks may occur at one of three stratigraphic levels:

(1) As part of the pre-Caracas basement complex.

(2) Contemporaneous with part of the Caracas group sedimentation but separated geographically.

(3) Overlying the Caracas group, that is, above the Tucutunemo formation, but predating the main period of deformation. In this case too their eruption might have taken place in a geographically separate area.

The distribution and structure of the Villa de Cura group parallels that of the metamorphic formations of the Caracas group to the north. Were these rocks part of the pre-Caracas group basement, the geographical distribution would not necessarily be expected to conform to the pattern of the younger rocks. This is partly confirmed by the fact that all basement outcrops south of the mountain belt (and also basement rocks recorded in boreholes) are unlike the Villa de Cura rock types. Furthermore, had the volcanic rocks been part of the provenance that supplied the sediment for the Caracas group, one should expect to find pebbles of the mafic volcanic rocks in the Las Brisas and succeeding formations. None have been observed. On the other hand if the green rocks were submerged under the transgressing epicontinental sea, they should now be covered by a thick wedge of Caracas group metasedimentary rocks. No such occurrences are known, nor is there any evidence to suggest that they formerly existed but have since been stripped off by erosion. Accordingly the first alternative is considered unlikely.

The similarity between the metatuffs of the Los Naranjos volcanic rocks and those of the El Caño formation, lowermost unit of the Villa de Cura group, at first suggested to the writer that the two volcanic sequences might be the same formation. This belief was fostered by their geographic proximity and by the fact that the same type of metavolcanic rock appears as tiny upfaulted blocks in the Paracotos formation which covers the area between the outcrops of the two (Pl. 1, K14). However, equating the Los Naranjos and El Caño formations poses certain problems, the nature of which may be best appreciated by further consideration of the conditions of deposition during Tucutunemo time.

It was suggested that the provenance of Tucutunemo sedimentation lay to the south and that the sediments had been transported for short distances only. Had the Tucutunemo conglomerates been brought across the El Caño volcanic rocks, conglomerates ought to occur within the Villa de Cura group, specifically near the upper contact of the El Caño formation. No such occurrences were noted despite careful mapping. One way of getting around this difficulty is to suggest that the conglomerates were swept around the east and west ends of the Villa de Cura volcanic pile. However the volcanic rocks appear to extend eastward at least 120 km to the bay of Higuerote and westward about 80 km toward El Pao (Hess, 1960, Fig. 2, C5). It is impossible to explain the composition and textures of the conglomerates in terms of transportation over such distances. Moreover it is unlikely that coarse feldspathic conglomerates could have been transported such distances in a marine environment. That the volcanic rocks were deposited subaqueously is indicated by the structures and textures of the volcanic sedimentary rocks. Also, had the volcanic rocks been exposed to subaerial erosion, pebbles of the volcanic rocks ought to occur in the Tucutunemo conglomerates, but none were observed. The suggestion that the Tucutunemo conglomerates were derived from the north cannot be countenanced, as it implies the existence of a major unconformity below the Tucutunemo formation, for which there is no evidence.

The only alternative therefore is to view the Villa de Cura volcanic rocks as being younger than the Tucutunemo formation. Under this hypothesis the Los Naranjos and El Caño volcanic rocks might be of related origin, the latter representing a resumption or continuation of the same type of volcanism. Comparison of the lavas in thin section shows that the resemblance between the two volcanic sequences is limited to a superficial similarity of the finely laminated tuffaceous facies. The lavas themselves are different. The Los Naranjos lavas (*see* MacLachlan, Shagam, and Hess) have a fine-grained felted texture related to colorless amphibole fibers in a turbid opaque groundmass of altered glass containing fine plagioclase

microlites. Phenocrysts of plagioclase (sparse) and augite (very rare) were observed. The El Caño lavas are coarser-grained rocks best described as augite andesites and spilites (*see* petrographic descriptions of El Caño rocks).

The view that the Villa de Cura group is post-Tucutunemo is supported by the serpentine intrusive bodies along the Villa de Cura-Tiara line. The present location of these masses is best explained in terms of a flat-lying sheet or sill of serpentine later dissected and deformed by faulting. Dengo and Smith both report that serpentinites along the coast northwest of Caracas and in the San Pedro area (Hess, 1960, Fig. 2, G2) are conformable with the bedding of the schists. The serpentinites appear to have been injected approximately at the contact between the Las Brisas and Las Mercedes formations. Assuming that the proposed sheet in the Central Aragua area was also injected conformably, some stratigraphic deductions may be made.

Evidence concerning the stratigraphic level of intrusion of the ultramafic masses is as follows:

(1) Smith described small serpentine bodies intrusive into Paracotos rocks (= writer's Tucutunemo formation) to the west and southwest of Charallave (Hess, 1960, Fig. 2, H3).

(2) The Loma de Hierro serpentine (Pl. 1, N20–O24) appears to be concordant in Tucutunemo rocks close to the upper contact of the Los Naranjos volcanic member.

(3) A small serpentine body west of Loma de Hierro (Pl. 1, N18) apparently intrudes the Tucutunemo formation at the top of the Los Naranjos volcanic member.

(4) Apart from the Agua Fria serpentine (Pl. 1, K20) no serpentines intrusive into the Villa de Cura group were observed. The Agua Fria mass is close to the lowermost exposure of the Villa de Cura group and has probably been reinjected in the solid state up to its present position.

These facts suggest that the serpentine was intruded at a stratigraphic level located in the Tucutunemo formation at or just above the upper contact of the Los Naranjos volcanic member. On the other hand the zone of intrusion was below the Villa de Cura group. The serpentines may have been intruded as a swarm of sheets at slightly different stratigraphic levels or alternatively as one huge sheet which locally displayed crosscutting relationships. It is suggested that faulting during and after the main deformation dissected the sheet and was responsible for subsequent local reinjections of some of the ultramafic masses. The large serpentine masses such as the Macuaya intrusive mass (Pl. 1, G4) may represent part of the original sheet now exposed at the surface.

The reconstruction of the serpentines as here proposed is diagrammed in Figure 6. If correct, the reconstruction confirms the belief that the Villa de Cura group is younger than the Tucutunemo formation. The reader is reminded, however, of the initial premise that the serpentine is a concordant body.

There is little evidence available to permit accurate reconstruction of the structural relationship which the Villa de Cura volcanism bears to the Caracas group. Speculation provides the following possibilities (Pl. 7):

(1) As the present geographic distribution of formations indicates, the Villa de Cura group may have been erupted south of the Tucutunemo formation. Possibly the close of Tucutunemo sedimentation was related to subsidence of the southern sedimentary provenance and was followed by submarine eruption of the volcanic rocks. Under this hypothesis a parallel may be drawn with other parts of the Caribbean island arc. Possibly the curvature of the deforming belt in Venezuela is such that the concave side lies to the south. In this case the volcanism could be compared to that of the Lesser Antillean region (and island arcs generally) with volcanism located on the concave side of the arc. The analogy may be extended inasmuch as the geographic relationships of the Los Narranjos and Villa de Cura volcanic rocks conform to Christman's (1953) suggestion that as a result of successive episodes of volcanism and deformation successively older volcanic rocks are encountered as one approaches the region of greatest deformation.

(2) Possibly the site of eruption of all the volcanic rocks was north of the present outcrop of the Tucutunemo sedimentary rocks, specifically in the vicinity of the metadiorite intrusive masses located along the northern border of Plate 1. The diorite and later soda granite intrusions may represent the intrusive facies of the mafic volcanic rocks, and the keratophyric metatuffs (?) of the Santa Isabel formation, respectively. This suggests eruption of the Los Naranjos volcanic rocks to the north followed by the derivation of the Tucutunemo conglomerates from a basement provenance located not far to the south. Later, renewed (Villa de Cura) volcanism to the north was of such volume as to cover the Tucutunemo formation and

extend itself far southward. The major question here concerns the proposed petrogenetic correlation of mafic volcanic rocks with dioritic intrusive masses. The proposal should not be immediately dismissed. Some of the diorites contain augite; furthermore their higher SiO_2 content could be related to contamination by quartzose host rocks.

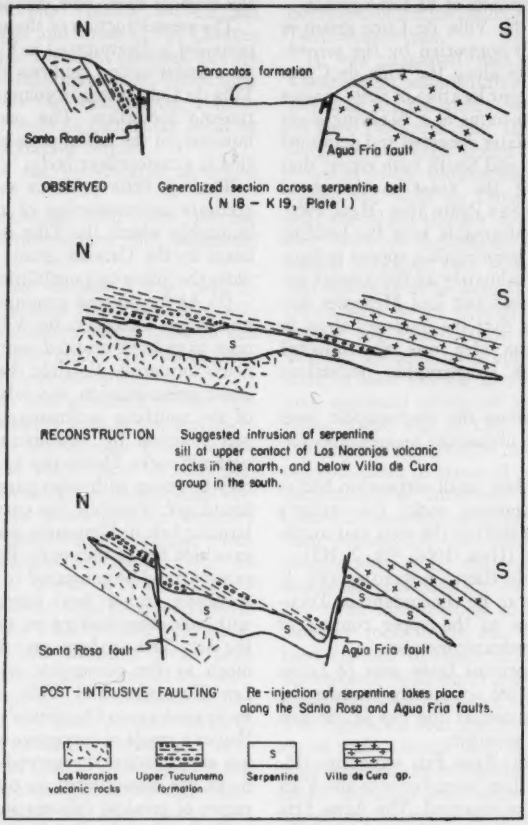


FIGURE 6.—POSTULATED SERPENTINE SILL BETWEEN THE TUCUTUNEMO FORMATION AND THE VILLA DE CURA GROUP
Relationship suggests that the Villa de Cura group is younger than the Tucutunemo formation

Whichever theory of origin is proposed to explain the Villa de Cura group, it can be said that the volcanic rocks were erupted subaqueously, as evidenced by a multiplicity of such sedimentary structures as graded bedding and scour-and-fill and the occurrence of pillow lavas. The absence of coarse clastic material of basement type indicates that the southerly sedimentary provenance was far distant or submerged. The abundance of carbonaceous material, especially in the El Chino formation, implies that anaerobic deep-water conditions prevailed for at least part of Villa de Cura time. Evidence suggests that the deposition of the Villa de Cura group was not continuous. The basal El Caño formation includes lavas that are best described as andesites, although spilitic basalts also occur. A second period of volcanism began with extrusion of the spilitic tuffs and lavas of the El Chino formation, continuing into and attaining a climax in the extrusion of the thick pile of lavas of the El Carmen formation. The final Santa Isabel phase is decidedly more felsic and possibly represents keratophyre tuffs of unknown source.

The diorite intrusive masses mapped by

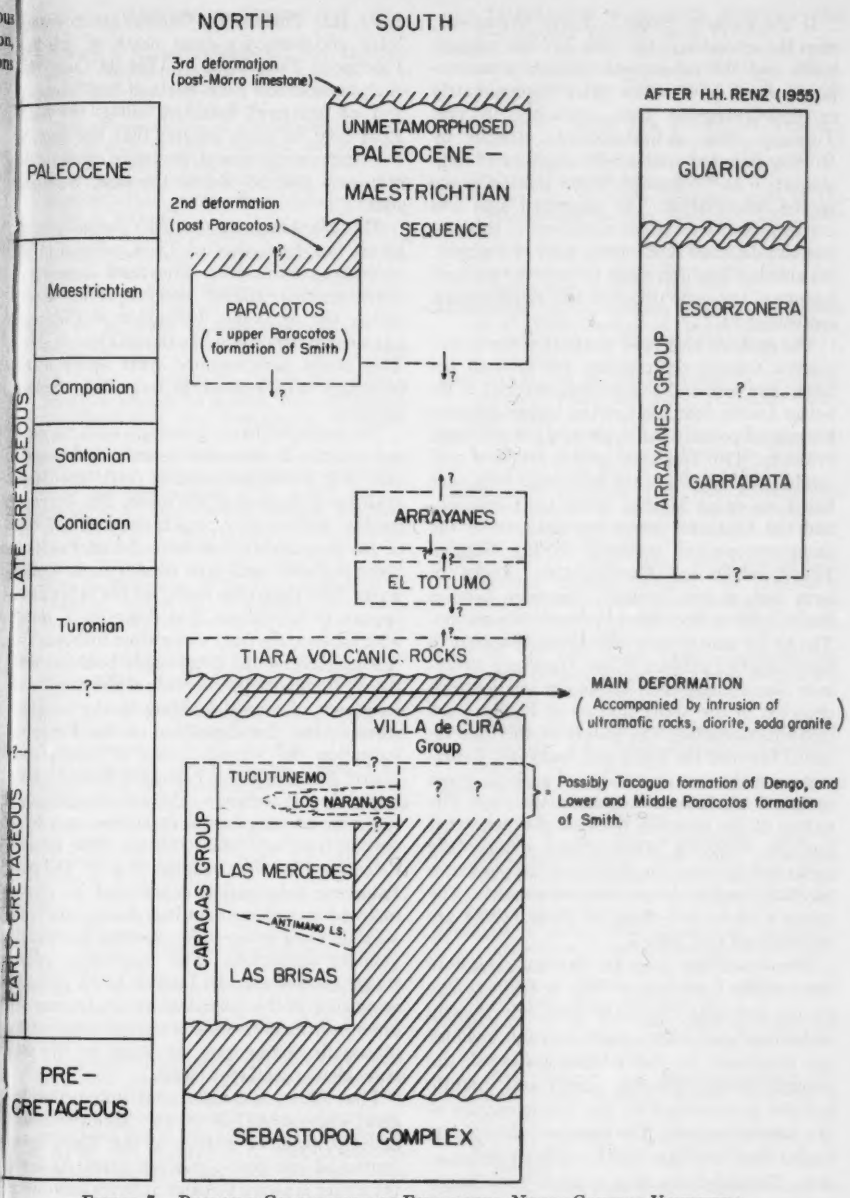


FIGURE 7.—PROPOSED CORRELATION OF FORMATIONS, NORTH-CENTRAL VENEZUELA

Smith (1953, p. 35) and MacLachlan (*in* MacLachlan, Shagam, and Hess, 1960) intrude the Las Brisas and Tucutunemo formations. Smith noted that the so-called soda granite dikes in the area northeast of Tiara appear to cut the main diorite mass. Both the diorite and the soda granite were intruded before or during the main period of deformation.

If the Caracas group is Early Cretaceous, then the extrusion of the Villa de Cura volcanic rocks and the subsequent regional metamorphism must have taken place approximately in mid-Cretaceous time, certainly in pre-Turonian time. Adjustment to stresses by faulting followed, and a new sequence of sedimentation and volcanism began leading to the second deformation. The suggested ages and correlation of formations contained in this section are depicted in the lower part of Figure 7. An attempt has been made to show the geologic history of the same period in the diagrammatic sections of Pl. 7.

The geologic history of the part of the stratigraphic column representing the interval between the first and second deformations is far better known than that of the earlier segment because of positive lithologic and paleontologic evidence. Two reference points are now well established. These are the Arrayanes beds near San Juan de los Morros, which are Coniacian, and the Paracotos formation and part of the unmetamorphosed sequence in the Guarico Valley, which are Maestrichtian. Rocks of both age groups contain abundant pebbles derived from the Tiara volcanic formation. The El Totumo limestones and shales appear to have supplied pebbles to the Arrayanes formation. Accordingly the relative age relationships depicted in the upper portion of Figure 7 are well substantiated. The nature of the time interval between the Tiara and Arrayanes formations is unknown; certainly no geologic event of major significance separates the two. The nature of the intervals between the Arrayanes and the overlying Maestrichtian sedimentary rocks and between the latter and the paracotos phyllitic shales have been discussed. The writer's views and those of Renz (1955) are summarized in Figure 7.

The formations may be distinguished from those of the Caracas and Villa de Cura groups by the fact that they have been only slightly metamorphosed. Also, mafic volcanic pebbles are dominant in the conglomerates of the younger group, whereas quartz and granitic pebbles predominate in the conglomerates of the older formations. The history of this episode begins after the main mid-Cretaceous deformation. Thereafter the first event of prominence was the submarine eruption of the Tiara lavas across a basement composed of the Villa de Cura group. The centers of volcanism possibly constituted a volcanic archipelago along the Villa de Cura-Charallave line (Hess, 1960, Fig. 2, F3, H2). Possibly the Caracas group was uplifted and formed a coast north of this line. Patches of Tiara lavas at Villa de Cura, near the morros of San Juan, north of San Sebastián and at scattered localities along the Santa Rosa road to Tiara suggest that the lavas at one time covered almost the entire extent of the map area and beyond to the east, west, and south.

This blanketing of the older formations explains the dominance of Tiara pebbles in the succeeding formations. The thick deposits of coarse-grained graded bedded rocks constituting the Arrayanes formation of Coniacian age suggest deposition in a trench close to shore. This might have resulted from uplift in the mountain area related to large-scale faulting activity.

The geologic history continues with the deposition of the Paracotos sediments in the mountain belt contemporaneously with the Maestrichtian deposition to the south. The degree of sorting, sedimentary structures, and lithology of the Maestrichtian rocks in the south clearly point to stable shelf-type conditions in shallow water. The Paracotos rocks, on the other hand, appear to have been laid down in a trough with moderately deep water close inshore. This is suggested by the large single boulders scattered throughout the phyllitic shales and by the frequency of graded bedding in the conglomerates. After the deposition of the Paracotos formation the second period of deformation began; it ceased before Paleocene sedimentation began. In the section on the unmetamorphosed rocks the consanguineous deposition and deformation from late Maestrichtian time to post-Paleocene time were detailed (Fig. 5). The post-Paleocene deformation culminated in, or was followed by, intense faulting, during which the Villa de Cura group was upfaulted against the younger formations. The mountains constituting the Serranía del Interior block probably originated in this period of uplift. During this same post-Paleocene deformation, some of the ultramafic bodies were reinjected in the solid state along prominent faults.

The Tiara volcanism constituted the last great outpouring of lavas. Minor volcanic activity, possibly related to the Tiara lavas, continued into post-Coniacian times. So far as the writer is aware volcanic activity terminated before the Maestrichtian.

Following the post-Paleocene deformation the processes of weathering and erosion set in that led to the present geomorphic character of the area.

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Manuscript Received by the Secretary the Society, July 8, 1958

Princeton Investigations of Caribb Geology No. 12

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 71, PP. 303-318, 2 FIGS., 4 PL. MARCH 1960

HIGH-TEMPERATURE ALPINE-TYPE PERIDOTITE FROM VENEZUELA

BY D. B. MACKENZIE

ABSTRACT

The Tinaquillo peridotite is the least serpentinized of the ultramafic masses included in the N. 75 E.-trending belt of Cretaceous metamorphic rocks in Northern Venezuela. It is a south-dipping tabular mass of intensely crushed and foliated dunite bounded on the north by a south-dipping regional thrust fault and on the south by regionally metamorphosed hornblende-quartz-plagioclase gneisses. Near the intrusion, these gneisses have been contact-metamorphosed by the dunite to garnet-augite-hornblende-andesine gneisses. Large tabular masses of gabbroic composition within the peridotite are interpreted as inclusions of contact-metamorphosed country rock. The peridotite contains thin hornblende and pyroxene layers parallel to the foliation and, in addition, remarkable lath-shaped orthopyroxene phenocrysts flattened in the planes of foliation and oriented dimensionally and crystallographically parallel to one another. These laths were formed by the stretching-out of primary equant-shaped phenocrysts, probably during final-stage solid intrusion of the peridotite.

The structure and composition of the pyroxene and garnet minerals in the contact rocks indicate that the temperature of intrusion was between 800°C. and 1000°C. During cooling, some of the thin pyroxene layers were altered hydrothermally to hornblende. Later and at still lower temperature, a belt of dunite along the Manrique thrust fault was altered to serpentinite and asbestos.

The other peridotites in the coastal range of northern Venezuela, which are moderately to intensely serpentinized, have no contact metamorphic aureoles, and some show conflicting age relationships toward the country rocks. Repeated upward movement during successive orogenies may explain these phenomena associated with serpentinites both in Venezuela and elsewhere.

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Introduction

The peridotite-serpentinite association of alpine mountain systems has attracted interest because of the general absence of associated high-temperature contact aureoles. A number of papers have attempted to explain the enigma presented by the absence of noticeable contact effects about magnesium-silicate plutons with high melting temperatures (Benson, 1926; Hess, 1938a; Bowen and Tuttle, 1949). Hess (1938a) has suggested that an aqueous ultramafic magma could exist at relatively low temperatures. However, Bowen and Tuttle (1949) in their experimental study of the MgO-SiO_2-H_2O system, to which natural peridotites belong, found that no liquid phases exist below 1000°C., the upper limit of their investigations. Bowen (1917, p. 237) suggested that intrusive peridotites are emplaced as masses consisting of olivine crystals lubricated by a small amount of magma. In light of his later experimental evidence, he revised his hypothesis in such a way that interstitial water vapor replaces magma as the lubricating fluid.

However, the present paper is only indirectly concerned with the question of liquid versus solid emplacement of magnesium-silicate rocks. It deals rather with the structural petrology and temperature of intrusion of one of those rare peridotites[1] that does have an authentic high-temperature contact aureole. The application of the study to hypotheses relating peridotite intrusions to mountain building is discussed at the end of the paper.

The field work was done as part of the mapping of the North Cojedes map area of Northern Venezuela during the summers of 1951 and 1952. The project was carried out under the Ministerio de Minas e Hidrocarburos, Caracas. The laboratory work was financed in part by Princeton University and in part under an Office of Naval Research Contract (N6Onr-27008) with Princeton University.

The writer is indebted to the director, A. Schwarck Anglade, and the staff of the Dirección de Geología for their co-operation in furnishing the necessary photographs, maps, equipment, and transportation and for the use of their facilities in Caracas. Grateful acknowledgment is made to G. Zuloaga and G. R. Heyl of Creole Petroleum Company for their loan of a jeep to the author for the 195 field season. The writer is indebted to J. C. Maxwell, A. F. Buddington, H. S. Yoder, R. Dana Russell, Charles H. Smith, H. W. Fairbairn, and H. H. Hess for a critical reading of the manuscript. He is particularly indebted to H. H. Hess for many helpful suggestions throughout the course of the work.

Geologic Setting

The southwest extension of the Caribbean island-arc system (Hess, 1938b) is the range of mountains trending west along the north coasts of Trinidad and Venezuela as far west as Barquisimeto (Aguerrevere and Zuloaga, 1937; Dengo, 1953; Hess and Maxwell, 1949; 1953; R. J. Smith, 1953; MacLachlan, Shagam, and Hess, 1960; Shagam, 1960; Bucher, 1952. *See* Hess, 1960, Fig. 2.) Whereas the islands in the Lesser Antilles are composed of unmetamorphosed Tertiary sedimentary and volcanic rocks, the coastal mountains of Venezuela are underlain mainly by Cretaceous (and possibly Jurassic) mica schists, calcareous schists, limestones, graphitic phyllites, graywackes, and basalts resting on pre-Cretaceous granitic rocks. Broad open folds trending N 75 E. constitute the major internal structure of the mountains. The folds, however, are somewhat masked by a widespread moderate to intense contortion of the schists and phyllites. The metamorphic rocks are bounded on the south by moderate to steep north-dipping thrusts which trend parallel to the mountains. Most of the north boundary is concealed by the Caribbean Sea, but near Maiquetia Dengo (1953) found a south-dipping thrust zone.

Included in these metamorphic rocks is a belt of ultramafic rock masses of the sort found in alpine-type mountains the world over (Benson, 1926; Hess, 1939). The geology of North-Central Cojedes, which has been discussed in detail elsewhere (D. B. MacKenzie, 1954, unpub. Ph.D. thesis, Princeton Univ.), is shown in Plate 1. The oldest rocks in the area probably are the hornblende-oligoclase gneisses and albite-quartz rocks cropping out extensively in the central and southern parts of the area. They are intruded by granitic rocks north of Tinaco and elsewhere, and extensive

[1] Others occur in Western Canada (Roots, 1954 p. 133) and in the Gaspé Peninsula, Quebec (Alcock, 1926; Osborne and Archambault, 1948), and possibly also in the Pyrénées (Lacroix, 1900), in the Urals (Wyssotzky, 1913), and in Newfoundland (C. H. Smith, 1958).

migmatization can be seen in the excellent exposures of the Río Tinaco. At one time it seemed possible to correlate these gneisses with the Villa de Cura group in Aragua (Shagam, 1960). However, if Shagam's tentative conclusion that the Villa de Cura group is younger than the Caracas group is correct, this correlation cannot be made. A basal conglomerate lying on the gneisses is well exposed southeast of Aguadita in a small erosional remnant containing both granite and gneiss pebbles. Elsewhere graphitic phyllites and dark metalimestones overlie the gneisses. The basal conglomerate, phyllite, and metalimestone can probably be correlated with Shagam's (1960) Tucutunemo formation (Hess, personal communication, 1959).

The quartz-biotite schists exposed in the northeastern part of the area are correlated with the Las Brisas schists (Dengo, 1953; R. J. Smith, 1953) of probable early Cretaceous age on the basis of lithologic resemblance.

In late Cretaceous to Paleocene time basaltic (and andesitic?) volcanic rocks were extruded along the southern margin of the mountains. During or following the volcanism, the quartz-biotite schists were thrust southward over the phyllites; the schists, gneisses, and phyllites were then upthrust northwestward and southward over the upper part of the phyllite section and the unmetamorphosed Upper Cretaceous-Paleocene gray shales, respectively.

The hornblende-quartz-oligoclase gneisses were intruded by the Tinaquillo peridotite, the second largest and least serpentinized peridotite in the Coast Range, prior to the thrusting. It is located just west of the town of Tinaquillo, which is 52 km southwest of Valencia (*see* Hess, 1960, Fig. 2). This peridotite is a large southwest-dipping tabular mass or sill, at least 3 km thick, which crops out over an elliptical area 13 by 5 km (*see* Pl. 4).

Previous Work

As early as 1890, samples of asbestos were sent from Venezuela to an international exhibition (Davey, 1947). However, no active interest was taken in the deposits at Tinaquillo until 1932, when exploration began under the supervision of W. Grenouillet. The only previous geological study of the peridotite was published by Aguerrevere, Zuloaga, and Tello (1937). This paper correctly interpreted the general form and petrology of the peridotite. The present author differs with it only in the interpretation of certain layers and masses of gabbroic composition which had been considered differentiates of the peridotite magma.

Description

General Statement

Nonfeldspathic rocks make up about 85 per cent of the Tinaquillo peridotite. Of these, more than 90 per cent are unserpentinized dunite. The remainder are serpentinized dunite, serpentinite, pyroxenite, pyroxene and amphibole layers, and granitic dikes, in order of abundance. The dunite, which everywhere has been intensely mylonitized, contains up to 10 per cent lamellae-bearing enstatites, both as equant grains and as remarkable long laths which are flattened in the planes of schistosity and crystallographically and dimensionally oriented. In many places, the dunite contains thin layers of enstatite, amphibole, or both, parallel to the foliation. The distribution of serpentinite is related to two structural loci: the Manrique thrust fault, and the contacts between dunite and pseudogabbro. Most of the serpentinite and all the asbestos deposits of potential commercial value occur in a narrow belt along the Manrique thrust fault.

Included in the peridotite and underlying about 15 per cent of the area are large tabular masses having a hypersthene-gabbro composition and a gneissic granoblastic texture, which are here designated "pseudogabbros." Large lamellae-bearing augite and hypersthene crystals and rare pyrope-almandite garnets occur in the gabbroic masses in a few localities.

Along the southern or upper contact of the intrusive mass, hornblende(green)-quartz-oligoclase gneisses of the country rock have been metamorphosed to garnet-hornblende (brown)-augite-andesine gneisses.

Dunite

Most of the dunite contains more than 95 per cent olivine; nearly all of it contains more than 90 per cent olivine. The remainder is composed largely of enstatite, with minor amounts of chromite and in places augite, amphibole, magnetite, chrysotile, and antigorite. Intense mylonitization has imparted to the rock a foliation which is visible only on

the outcrop surfaces, where it has been made conspicuous by differential weathering. Thin layers of pyroxene or amphibole, conspicuous on both fresh and weathered surfaces, are not uncommon. As seen in thin section, the olivine

In those thin sections cut normal to long dimension of the laths, the (100) parti and the clinopyroxene lamellae comm exsolved parallel to this parting are conspi ous. Whereas the equant pyroxenes are

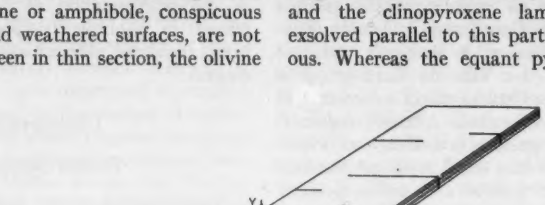


FIGURE 1.—SKETCH OF AN ORIENTED ENSTATITE LATH IN DUNITE
The lath is flattened in a foliation plane.

occurs in angular strained grains ranging from 0.01 to 0.5 mm, although grains larger than 0.2 mm are uncommon. The olivine has a refractive index $N_x = 1.656$, approximately, which corresponds to a composition of Fo 90 (Poldervaart, 1950). Chromite, in disseminated light-yellow-brown ragged-edged grains, and interstitial serpentine each usually constitute less than 1 per cent of the dunite.

The enstatite occurs in two ways: as 1–5-mm equant dark-green grains and, more strikingly, as long thin oriented laths flattened in the planes of foliation. Both habits may occur in the same hand specimen (Pl. 2). The laths are 10–50 mm in length, 1–4 mm in breadth, and a fraction of a millimeter in thickness. Although the length of the laths averages 10 times the mean dimension of the equant grains, the difference in volume between individual lath-shaped and equant-shaped pyroxenes is no greater than the differences in volume among the equant-shaped grains themselves.

Within each hand specimen and within each area of outcrop, the enstatite laths show a high order of linear as well as planar parallelism. The direction of elongation is parallel to minor fold axes in adjacent masses of pseudogabbro. Furthermore, as shown in Figure 1, the long dimension of the laths is in all cases crystallographic c, and the plane of flattening is (100).[2]

formed and ragged about the edges, the la are generally unbent crystals.

Determinations of 2V made on 10 enstat grains in five enstatite-bearing dunites f into the range 83.0° to 80.0° positive, co sponding to compositions in the range 90.0 to Mg 92.0 (Hess, 1952). Refracti index and 2V determinations carried out samples of equant and lath-shaped enstati in the same rock show they are of identi composition.

Serpentinite and Asbestos[3]

In very thin zones adjacent to some of t pseudogabbro masses and in a broader b along the Manrique thrust fault the peridot has been moderately to intensely serpentiniz The serpentinite is composed mainly of an gorite, the alteration product here of olivi as well as enstatite. In addition, small veinl of chrysotile asbestos are found in the serpe tinite, particularly in the zone along the Ma

[2] A preliminary fabric study of the olivines associated with the pyroxene laths in the less-deformed dunite indicates that the (100) poles of the olivi have a preferred orientation parallel to the (0 poles of the laths and that the (001) and (010) po of olivine each form maxima normal to this di tion. In view of the conclusion reached in this pa that the enstatite lineation is parallel to the mo ment direction, this observation supports Turn (1942) conclusion that the pole to (100) is one of principal glide directions in olivine.

[3] The serpentinite and asbestos are mentio only briefly here. They are discussed in greater tail elsewhere (D. B. MacKenzie, 1954, unp Ph.D. Thesis, Princeton Univ.).

rique thrust fault. The two asbestos-producing areas, El Tigre and La Montañita, and all asbestos showings of potential commercial value are located in this belt.

The occurrence of serpentinite near contacts of the peridotite with country rock indicates that the necessary water was derived either directly from the country rock during a late stage in the cooling of the intrusion or from later hydrothermal solutions circulating in the contact zones. It can be argued that the serpentinite along the Manrique fault was formed during cooling from waters derived directly from the rock originally adjacent to the peridotite on the northwest. According to this view, the Manrique fault, which is a regional feature at least 40 km long, subsequently passed through this zone subparallel to the contact between serpentinite and dunite. This appears fortuitous. More probably the serpentinite resulted from alteration of the dunite by later hydrothermal solutions moving in the fault zone.

The phyllite in a zone along the Manrique thrust fault is only mildly bleached and silicified. The absence of the talc and actinolite that one would normally expect in the adjacent country rock (Phillips and Hess, 1936) is attributed to postserpentinization movement along the fault zone.

Pyroxene and Amphibole Layers

Thin, sparsely distributed amphibole- and pyroxene-rich layers, most of which are oriented parallel to the dominant southward-dipping foliation, occur in most parts of the Tinaquillo peridotite. Layers have been found with the following compositions: (1) orthopyroxene with a very small amount of clinopyroxene or plagioclase; (2) augite; (3) equal amounts of augite and orthopyroxene (websterite); and (4) light-brown amphibole with or without a small amount of pyroxene. The first and last types are the most abundant. In addition, small elliptical plugs of enstatite pyroxenite, several tens of meters in diameter, occur, particularly in the west end of the intrusive body.

The layers range in thickness from a few millimeters to half a meter, although few layers are more than several centimeters thick. Owing to their greater resistance to crushing, the layers are everywhere more coarsely crystalline than the adjacent dunite mylonite. Most of the layers have a 0.5- to 1-mm even-grained cataclastic texture. The contact between the layer and the dunite is invariably sharp and regular.

Where orthopyroxene occurs, it has a composition between Mg 85 and Mg 90. Diopsidic lamellae are uncommon, and where present, they are much thinner than those in the disseminated orthopyroxenes. Most of the grains have strained interiors and ragged edges. Associated with the pyroxene layers are small amounts of green spinel and magnetite (?) and, in places, plagioclase and secondary amphibole. Chromite is nowhere found in the layers.

In the amphibole-rich layers, which are more abundant than the pyroxene-rich layers, relict pyroxenes may be present, but more commonly only a peculiar brown amorphous alteration mineral is present in addition to the amphibole. Table 1 shows the chemical composition and optical properties of the amphibole. The properties accord well with those of pargasite.

Although pyroxene and amphibole can crystallize together in both water-deficient and water-excess regions (H. S. Yoder, 1958,

TABLE 1.—CHEMICAL COMPOSITION AND OPTICAL PROPERTIES OF AMPHIBOLE SAMPLE NO. VT 250a (R 1940)

Eileen H. Oslund, Rock Analysis Laboratory, University of Minnesota, Analyst

Composition	Percentage
SiO_2	43.61
Al_2O_3	15.06
TiO_2	1.15
Fe_2O_3	1.59
FeO	5.14
MnO	0.08
MgO	16.53
CaO	11.80
Na_2O	2.78
K_2O	0.11
H_2O+	1.69
H_2O-	0.05
	99.59

N_x	1.643	± .001
N_z	1.659	± .001
2V	+82.4°	± 0.5°
$Z\wedge c$	19°	± 1°
Pleochroism	X	colorless
	Y	very light brown
	Z	very light brown

personal communication) at least some of the amphibole in these rocks appears to be younger than the pyroxene. In some thin sections, parts of pyroxene grains are replaced by amphibole. An origin of amphibole by hydrothermal replacement of pyroxene is thus indicated. The replacement probably took place within the stability range of the pyroxenes or at temperatures not far below the lower limit of stability of the pyroxenes (660°C. at 15,000 psi in the case of enstatite, according to Yoder, 1952) while supercritical aqueous fluids continued to move along the planes of schistosity.

The pyroxene-rich layers may also have been formed by hydrothermal solutions moving along foliation planes in the dunite at an earlier, higher-temperature stage. Bowen and Tuttle (1949) have suggested that most pyroxenites are formed from dunite in this way. An alternate hypothesis is that the pyroxene-rich layers are flow layers formed by mechanical segregation of pyroxenes originally disseminated in the dunite during emplacement of a "crystal mush."

Granitic Dikes

Small plugs and narrow dikes of granitic composition are found in most parts of the intrusive mass and are particularly abundant in the northeast part. Although a considerable variety of petrographic types occurs, most of the dikes are composed largely of plagioclase (An 10–20) with minor amounts of quartz and muscovite. The only talc-tremolite rocks in the area are found as narrow selvages along the walls of the dikes and masses.

Pseudogabbro

General description.—Rocks of gabbroic composition, here called "pseudogabbro," underlie more than 10 per cent of the area within the peridotite boundaries. The pseudogabbro occurs in large tabular masses which are concordant with the peridotite foliation in the south part of the intrusive mass and discordant in the north part. Contacts with the peridotite are sharp and commonly loci of intense shearing.

These gabbroic masses are composed of plagioclase, clinopyroxene, orthopyroxene, amphibole, magnetite, ilmenite, and rare spinel, garnet, and pyrite. The plagioclase constitutes 30 to 50 per cent by volume; the rest of the rock is made up of 20 to 35 per cent amphibole, about 15 per cent clinopyroxene, a somewhat smaller amount of orthopyroxene, and a few per cent of disseminated metallic minerals. The grain size, which is remarkably uniform throughout the area, ranges from 0.2 to 0.8 mm in most rocks and is close to 0.5 mm in many. Most of the grains are anhedral, equidimensional, and unstrained, and nowhere were they seen interlocking. Segregation of the light and dark minerals into layers 1–2 mm thick imparts a pronounced foliation to most outcrops. Although the foliation is somewhat irregular, it tends to conform to the foliation in the surrounding dunite. In some places, the dark minerals form lenticles in a ground-mass of light minerals.

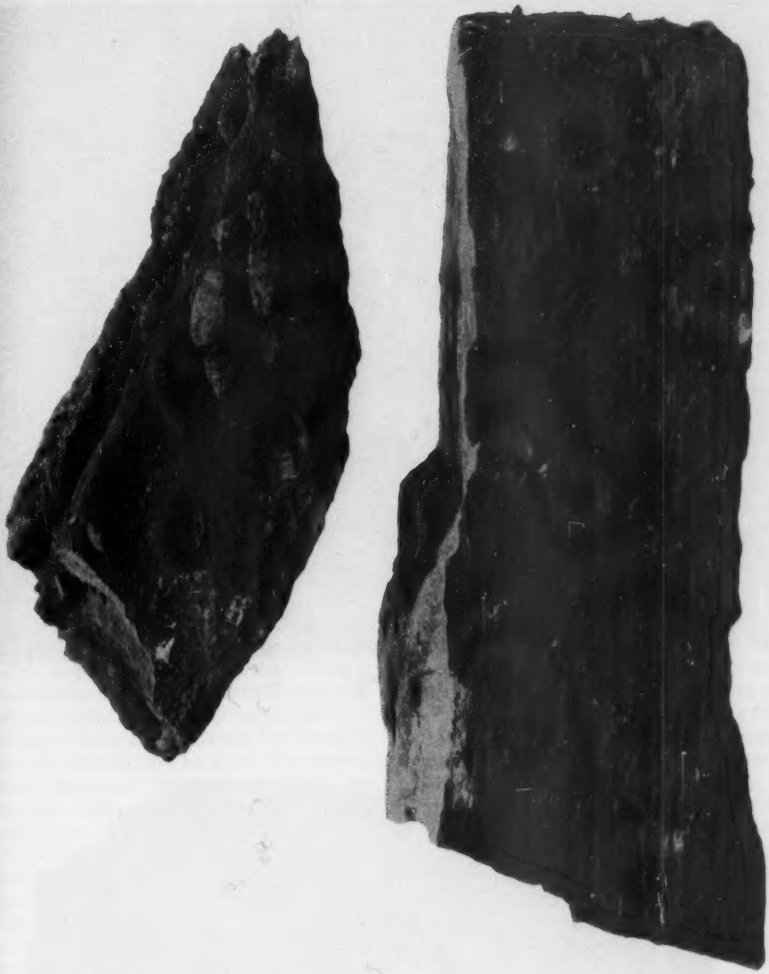
The rock, then, is a granoblastic gneiss, the product of crushing and recrystallization at moderate to high temperature (Buddington, 1939, p. 253). *See* Plate 3.

Plagioclase.—Plagioclase, An 50 to An 70, constitutes the feldspathic phase of the gabbroic masses. The compositions were determined by the measurement of N_x and N_z and the use of unpublished index-composition curves of J. R. Smith and H. H. Hess. The plagioclase has an average composition between An 55 and An 60. The range in individual samples, which probably represents zoning of crystals and which is determined from the composition equivalents of the minimum N_x and the maximum N_z, may be as much as 10 per cent but generally is less than 6 per cent.

Most of the plagioclase is polysynthetically twinned. No detailed study was made of the various types of twinning, but in some sections abundant twinning according to the pericline law and some according to complex twin laws was observed. Many grains are twinned in one part and untwinned in another. The

PLATE 2.—TWO SPECIMENS OF DUNITE WITH ENSTATITE LATHS

The oriented enstatite laths stand out on the weathered surfaces. In the smaller specimen, the foliation planes and the (100) plane of the laths are in the plane of the paper. In the larger specimen, the foliation planes and the (100) plane of the laths are perpendicular to the paper and the laths appear as thin resistant ridges. In both specimens, crystallographic c of the laths is parallel to the long dimension of the page. Equant enstatites are also present. Scale: 0.8 × natural size



TWO SPECIMENS OF DUNITE WITH ENSTATITE LATHS

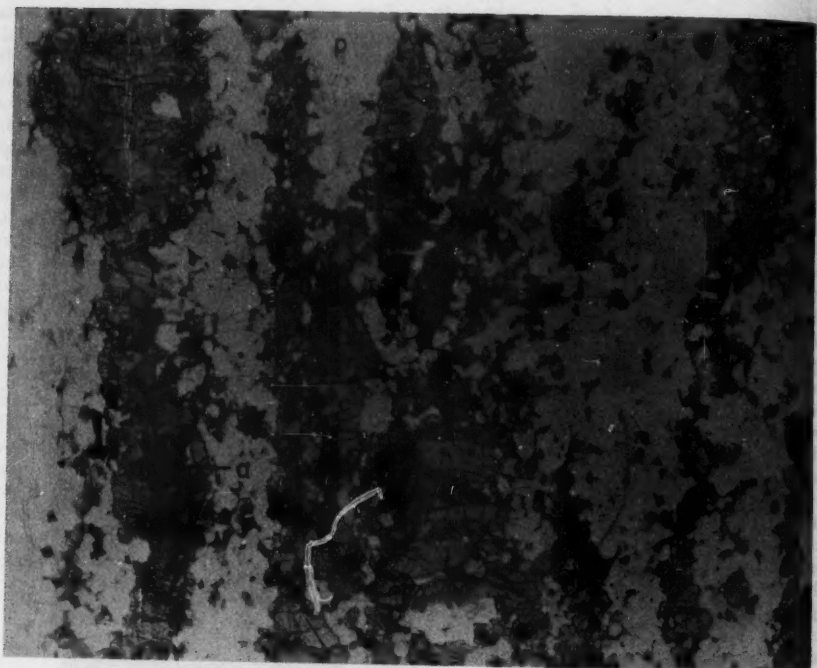


FIGURE 1

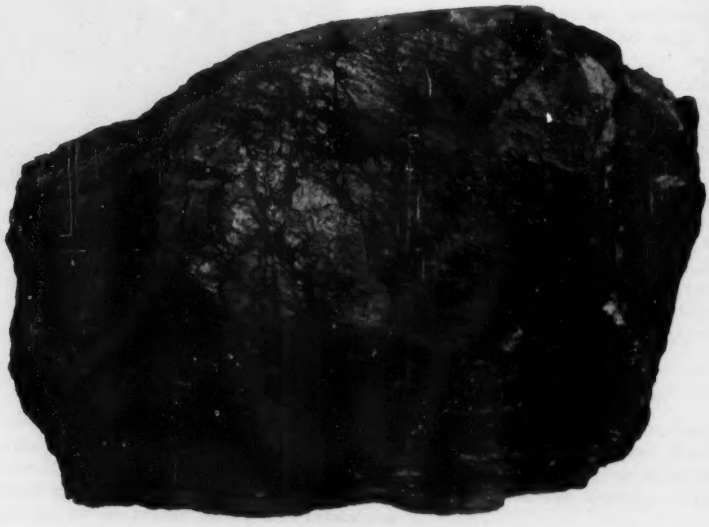


FIGURE 2

SPECIMENS OF PSEUDOGABBRO

twinned area not uncommonly forms the core of the grain. Where a slight zoning is present, the more calcic area is closer to the core.

Pyroxene.—In most of the pseudogabbro masses, clinopyroxene constitutes about 15 per cent of the rock and is about twice as abundant as orthopyroxene, although in some specimens orthopyroxene is more abundant and may even constitute the entire pyroxene phase. Refractive-index and 2V determinations on several clinopyroxene grains indicate a composition in the upper-left corner of the augite field of Poldervaart and Hess (1951). The associated orthopyroxene grains have compositions in the range Mg 62 to Mg 85 with most grains between Mg 70 and Mg 78 (2V composition curves of Hess, 1952). In most of the pseudogabbro specimens, about half the pyroxene is replaced by a light-brown amphibole, to be described hereafter.

Conspicuous departures from the normal fine-grained textures of the pseudogabbro are scarce large eye-shaped orthopyroxene and clinopyroxene crystals as much as 5 or 6 cm in length (Pl. 3, fig. 2). Whereas the groundmass pyroxenes do not contain exsolution lamellae, most of these large pyroxenes do. The lamellae consist of clinopyroxene if the host is orthopyroxene and of orthopyroxene if the host is clinopyroxene. Both kinds of lamellae are now partly or wholly replaced by amphibole.

Although these large crystals are certainly clastic with reference to the latest deformation, in which they were distorted and broken up around the edges, a more important consideration is whether they are relict from an originally very coarse-grained or porphyritic gabbro or whether they grew in a solid medium as porphyroblasts. Unfortunately, criteria for distinguishing between the two are rather unsatisfactory. However, the suggestion is made that they grew as porphyroblasts for the following reasons:

(1) Were they clasts of igneous gabbros, one might expect them to be rather evenly distributed throughout the pseudogabbro masses, if not as grains measured in centimeters, certainly as lamellae-bearing grains in the groundmass. However, as pointed out, these lamellae-bearing grains, large or small, are scarce.

(2) The large grains, particularly the remarkable specimen in VT 232 (Pl. 3, fig. 2) have not only the typical "eye" shape but also the characteristic pressure shadows depleted in the phase constituting the porphyroblast (Ramberg, 1952). In this case, the shadows are rich in plagioclase. The possible significance of these large crystals is considered later.

Amphibole.—The amphibole, which is present in amounts ranging from 20 to 35 per cent, occurs both as discrete grains and as partial replacements of pyroxene grains. The amphiboles are, like those in the layers in the peridotite, brown—but a much deeper, more reddish brown. The pleochroic formula is: *X*, light brown; *Y*, *Z*, brown to reddish brown. The greater depth of color corresponds to a greater N_x, namely, 1.65 to 1.67. The optic angle is in the range 77° to 82° negative, and the average $Z \wedge c$ is 15°. The optical properties correspond in general with those of the hornblende group and in particular with those rich in the tschermakite molecule (Sundius, 1946).

Minor constituents.—Two polished sections of pseudogabbros each revealed about 10 per cent metallic minerals occurring in disseminated 0.08-mm grains with rounded or scalloped boundaries. Most of the grains are ilmenite, showing several stages of replacement by magnetite around the edges and along cracks. No exsolution structures were observed.

Small grains of a deep-red garnet, similar to that occurring in the southern contact aureole, were found in a few places. Considering its abundance in the contact rocks, garnet is remarkably scarce in the pseudogabbro masses.

Peridotite Contact Aureole

Along the southern margin of the Tinaquillo peridotite the hornblende-quartz-plagioclase gneiss country rock has been contact-metamorphosed to garnet-pyroxene-hornblende-plagioclase gneiss. The maximum breadth of the

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PLATE 3.—SPECIMENS OF PSEUDOGABBRO

FIGURE 1.—Photomicrograph of pseudogabbro specimen VT 231, which is very similar to VT 232 in Figure 2. Note the replacement of pyroxene by amphibole. Magnification 15 ×. Plain light; a, amphibole; c, clinopyroxene; h, hypersthene; p, plagioclase

FIGURE 2.—Photograph of pseudogabbro specimen VT 232, showing a large orthopyroxene crystal partly altered to brown amphibole. This crystal is interpreted as a porphyroblast. Natural size.

contact zone is about 4000 m (which is equivalent to a thickness of 1500 to 2000 m if the simple southward projection of the dip of the southern contact is valid). Owing to deeper weathering and poor exposures, however, the aureole is less well adapted to detailed petrologic study than the pseudogabbros described in the preceding section.

South of the contact zone, the country rocks are composed of interlayered hornblende-quartz-plagioclase gneisses and quartz-plagioclase rocks. The hornblende gneisses consist roughly of 50 per cent oligoclase, 25 per cent each of hornblende and quartz, and small amounts of chlorite, epidote, clinozoisite, apatite, and sphene. Segregation of hornblendes into layers several centimeters thick is common. The quartz-plagioclase interlayers range in composition from 90 per cent quartz to 90 per cent albite or oligoclase.

The south edge of the contact zone is marked by the appearance of sparse small red garnets which increase in size and abundance toward the peridotite. Most of the garnets are concentrated in a narrow zone along the peridotite contact. One sample of garnet has A_0 = 11.54 Å; N = 1.775; and Sp. G. = 3.73. These constants accord well with those of a magnesian pyralspite having about 10 per cent of the andradite molecule in solid solution (Winchell, 1951). However, without chemical analyses, it is difficult to designate the garnet composition with confidence.

Accompanying the appearance of garnet, the plagioclase composition changes from An 10–25 to An 40 and, nearer the contact, becomes as calcic as An 50. The outer edge of the aureole is also marked by a change in the color of the hornblende from green to brown, an increase in its optic angle (2V) from −(57° to 70°) to −(77° to 82°), and a decrease in its extinction angle (Z∧c) from 19° to about 15°. The brown hornblende in the contact zone is indistinguishable from that in the pseudogabbro masses. Augite may appear also on the outer edge of the aureole, although it is abundant only in the inner part of the contact zone.

Along the southern contact of the intrusive mass, the rocks are texturally and mineralogically similar to the pseudogabbro masses within the dunite itself. A common rock type has the composition: augite, 18 per cent; brown hornblende, 20 per cent; pyrope-almandite, 20 per cent; calcic andesine, 37 per cent; hypersthene, 2 per cent; and ilmenite and magnetite, 2 per cent. The following differences exist between the pseudogabbro masses and the inner part of the aureole: in many rocks of the contact zone, orthopyroxene is present in very small quantity or is absent, whereas in the pseudogabbro masses, it constitutes 5 to 15 per cent of the rock; there is no porphyroblastic development of either kind of pyroxene, and no lamellae-bearing augite whatever occurs in the contact zone; the plagioclase composition in the contact zone is in the An 45 to An 50 range, whereas in the pseudogabbros it is in the An 55 to An 60 range; garnets, although scarce in the pseudogabbros, are present in amounts up to 20 per cent in the contact zone.

The quartz-rich layers of the country rocks are largely obliterated in the inner part of the contact aureole.

Interpretation

Genesis of the Contact Aureole

The rocks south of Tinaquillo are designated as contact-metamorphosed country rocks principally on the following evidence: a gradation in the plagioclase phase from oligoclase in the hornblende gneisses through sodic andesine on the fringes of the contact zone to calcic andesine near the peridotite contact; a color change in the hornblende from green to brown; and the appearance of augite and pyrope-almandite, both of which increase in quantity from south to north. It will be shown that there must be, in addition, a large relative increase in MgO and CaO from south to north or from the outer to inner parts of the contact zone.

The augite-hypersthene-pyrope-almandite-hornblende-andesine rocks of the inner zone of the contact aureole do not fall into any of the subdivisions of the amphibolite, the pyroxene hornfels, or the granulite facies of Turner and Verhoogen (1951). In none of the fields shown are diopside, andesine, and pyrope-almandite stable together. Nor is this assemblage found in any published descriptions of metamorphic rocks. Probably the rise and fall of temperature during metamorphism was too rapid for the attainment of equilibrium. According to Turner (in Turner and Verhoogen, 1951, p. 475), rocks in which garnet is associated with hypersthene, diopside, plagioclase, and hornblende are probably in a state of chemical disequilibrium.

In any case the occurrence of pyrope-almandite in this environment is unusual.

Tilley (1926) has observed that almandite garnet usually develops under regional rather than contact-metamorphic conditions. In two respects at least, the conditions of formation of the contact assemblage at Tinaquillo differed from those about most granite plutons: (1) the environment was less hydrous; (2) a moderate to intense shearing force was in operation during the metamorphism. In both respects, the contact metamorphism at Tinaquillo is more closely related to regional than to normal contact metamorphism. The growth of magnesian pyralspite as a contact mineral could be attributed to either one or both of these special conditions.

Experimental work by Yoder (1952, p. 613; 1955, p. 520; 1958, personal communication) suggests that, although at sufficiently high pressures garnet may be stable whether excess water is present or not, at lower pressures garnet is probably stable only in the water-deficient region. Since the regional relationships do not suggest that the peridotite was intruded at a particularly deep level in the crust compared to magmatic granite plutons with contact aureoles, the water-deficient environment may well be the most important factor in explaining the garnet preservation.

In the absence of chemical data on the garnets and hornblendes, calculation of the chemical composition of the rocks cannot be attempted. Comparison of the average mineralogical composition of the country rock with that of the contact-metamorphosed country rock, however, shows that large amounts of CaO, MgO, and a smaller amount of FeO have been added to the rocks of the contact aureole.

With a hypothesis of CaO and MgO metasomatism of the contact rocks, a more than adequate source of the MgO is close at hand. The source of the CaO, however, is obscure. Possibly high-temperature (800° to 900°C.) aqueous fluids moving through an originally more CaO-rich peridotite were capable of taking both MgO and CaO into solution[4] and depositing them at lower temperatures in the contact zone.

An alternate hypothesis is that during metamorphism, chemical redistribution took place within the country rocks so that the inner part of the contact zone became enriched in CaO and MgO.

Much more detailed petrographic and chemical work would be necessary to show which of the above hypotheses is the more probable.

Genesis of the Pseudogabbros

The large masses of gabbroic composition within the peridotite were called norites by Aguerrevere, Zuloaga, and Tello (1937). Although some have the composition of true norites, most are more similar to hypersthene gabbros. Three hypotheses of origin are here considered. The masses are either: (1) feldspathic differentiates from a peridotitic magma (Aguerrevere, Zuloaga, and Tello, 1937); (2) parts or remnants of a gabbroic intrusion; or (3) included masses of contact-metamorphosed country rock.

Considering the first hypothesis: nowhere do rock types intermediate between the gabbro and peridotite exist, such as one might expect if the gabbro and dunite were related differentiates. All contacts are sharp, and the rock types are distinct and uniform. Furthermore, the plagioclase of feldspathic differentiates of peridotites is commonly much richer in the anorthite molecule than An 60; in addition, the differentiates are usually troctolites or at least olivine gabbros.

For a number of reasons, it is also unlikely that the gabbroic masses are parts of an igneous intrusion, either younger or older than the peridotite. Considering first the possibility that the gabbroic masses are younger than the peridotite, the most significant point is the absence of relict euhedral grains and interlocking texture. Since the area underwent only low-temperature crushing after the period of emplacement of the peridotite, and since the gabbroic masses are more competent than the surrounding peridotite, preservation of relict igneous texture would be expected, at least in a few places. In addition, if the large augen-shaped lamellae-bearing pyroxenes are porphyroblastic, as suggested earlier, the gabbroic rocks could not be younger than the peridotite because the peridotite would be the only possible source of the heat necessary for the growth of these high-temperature crystals.

In connection with the hypothesis that the gabbroic masses are remnants of an intrusion older than the peridotite, the possibility should also be considered that this intrusion

[4] A search through the literature on physicochemistry revealed no data on the solubilities of fluids in this temperature range. The only pertinent data are those of Bowen and Tuttle (1949), who found that the solubility of MgO in aqueous fluid at 400°–500°C. was below the detection level of their experimental apparatus.

caused the contact metamorphism around the peridotite and was the source of the apparent CaO and MgO metasomatism in the inner part of the contact aureole. In this consideration it is implied that the emplacement of the peridotite itself had litttle effect upon the country rock. Were this so, the peridotite would have little effect on the gabbro, and some of the igneous texture should be preserved. As pointed out, the gabbroic masses everywhere have a granoblastic texture. Furthermore, if this interpretation were correct, some contacts between the gabbro and the country rock should be preserved, even though apophyses might be obliterated by shearing along the contacts. Since the garnet-bearing gneiss in the inner part of the contact aureole is conspicuous and easily differentiated from the gabbroic masses, one would expect that the contact between the two would be visible somewhere either in the gabbroic masses or in the contact aureole. It would be remarkable, indeed, if the boundaries of the peridotite intrusion coincided with those of a preceding gabbroic intrusion.

Possibly, the gabbroic masses are part of an earlier intrusion which was incorporated in and reconstituted by the peridotite. However, since positive criteria of a magmatic origin are absent and since the evidence points strongly to the peridotite as the cause of the metamorphism of the country rocks to rocks of gabbroic composition in the inner part of the contact aureole, the writer favors the belief that the gabbroic masses are large inclusions of the contact-metamorphosed country rock. It is for this reason that the gabbroic masses are designated as "pseudogabbros" in the text.

Temperature of Intrusion

It will be recalled that, although garnets are abundant in the inner zone of the contact aureole of the Tinaquillo peridotite, they are scarce in the pseudogabbro masses. Their scarcity cannot be attributed to excess water within the peridotite, because both the anhydrous nature of the dunite and the arrested growth of the hornblende in the pseudogabbro attest to its relative dryness. On the contrary, garnets are scarce because the pseudogabbro was heated through and above their stability range, and almost all of the garnets formed during the process were later decomposed. Thus the garnets represent a phase that disappears in the direction of increasing temperature.[5]

The upper stability limit of garnet appears to be least in water-deficient regions at low pressures (Yoder, 1952, p. 613; 1955, p. 520). Therefore in order to establish a minimum temperature of intrusion, this case is the one to be considered.

Pyrope is believed to be stable, in the water-deficient region of the MgO-Al_2O_3-SiO_2-H_2O system, under a pressure of 15,000 psi, at 600°C.; its upper stability limit under the same conditions is thought to be less than 680°C. (Yoder, 1952, p. 613). Assuming that a moderate amount of the almandite molecule does not greatly alter these estimates, 600°C. is the probable minimum temperature attained by the pseudogabbro masses.

Relationships within the pyroxene group are useful in establishing the temperature of intrusion more closely (Poldervaart and Hess, 1951). It has been noted that, in contrast to most of the groundmass pyroxenes, all the large augen-shaped crystals in the pseudogabbros contain exsolution lamellae. It follows that these large hypersthene and augite grains grew in a temperature range in which small amounts of the augite and hypersthene molecules, respectively, could be taken into solid solution (Poldervaart and Hess, 1951). This material was exsolved as a result of the ordering of the structure during cooling. The nonlamellar material, which grew in the same chemical environment, crystallized or recrystallized at temperatures below the temperature range in which the foreign ions go into the structure in appreciable amounts.

H. H. Hess (Oral communication) believes that in the temperature range 700° to 1100°C., the higher the temperature, the greater the amount of augite and hypersthene that can be taken into the hypersthene and augite structures respectively.[6] Unfortunately no experimental data are available. However, the thickness and spacing of the lamellae in the hypersthenes are comparable to those in many hypersthenes from norites and gabbros, indicating that the amount of exsolved augite, and hence the amount originally in solid solution, is similar. Therefore like noritic

[5] Yoder (1952) has emphasized that the disappearance of a phase in the direction of increasing temperature is of much greater significance in geological thermometry than the appearance of a phase.

[6] Ca^{++} ions can enter the hypersthene structure up to 3.5 per cent of the total $Ca^{++} + Mg^{++} + Fe^{++}$

and gabbroic pyroxenes, the large augen-shaped crystals probably grew in the temperature range 800° to 1000°C. If these crystals are porphyroblasts as suggested, they provide an index of the temperature of metamorphism.

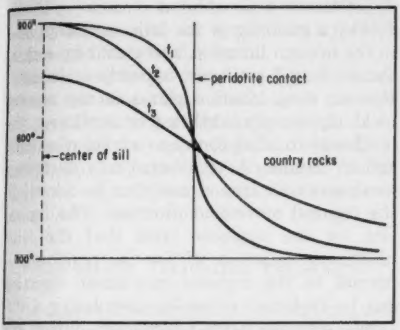

FIGURE 2.—TEMPERATURE DISTRIBUTION NEAR CONTACT OF PERIDOTITE
(After Lovering, 1935)

In summary, available data on the garnet and pyroxene groups indicate that the pseudogabbro masses were metamorphosed at a temperature greater than 600°C. and probably between 800° and 1000°C.

Lovering (1935) carried out a theoretical study of the dissipation of heat at intrusive contacts. Assuming the instantaneous intrusion of a tabular body into an infinite medium which is isotropic and has the same diffusivity constant as the intrusion, the temperature at the contact attains a temperature midway between the temperature of the central part of the intrusion and the country rock.

The country rocks into which the Tinaquillo peridotite was intruded are best grouped in the epidote-amphibolite metamorphic facies (D. B. MacKenzie, 1954, unpub. Ph.D. thesis, Princeton Univ.). According to Rosenqvist (1952), this facies represents a mean temperature of metamorphism of about 300°C. Then, if it is assumed that the peridotite was intruded during the regional metamorphism and that the peridotite temperature was not significantly higher than that of the enveloped pseudogabbros, the temperature distribution in Figure 2 results. The curves suggest that the inner part of the contact aureole attained a temperature of nearly 600°C. during the metamorphism.

Confirmatory independent evidence for a temperature of intrusion of the peridotite of 800° to 1000°C. is given hereafter.

Genesis of Lath-Shaped Orthopyroxenes in Dunite

Enstatites with a lath shape like those in the Tinaquillo peridotite have not previously been described. However, in photomicrographs of the dunite-mylonites of St. Paul's Rocks published by Tilley (1947), some enstatites flattened parallel to the lamellae are visible. Neither their shape nor orientation is discussed in the text.

The morphology and orientation of the Tinaquillo enstatite laths indicate two possible modes of origin: (1) they are porphyroblasts which grew during a period of movement along shearing planes, their peculiar shape resulting from growth in the direction of least resistance (principle of Wegsamkeit); or (2) they are phenocrysts which acquired their present shape and orientation through intracrystalline translation gliding.

A porphyroblastic origin is less probable because, if they were formed in this way, they might be expected to have a composition slightly different from that of the equant-shaped pyroxenes of the same hand specimen. Yet, index and 2V determinations indicate that their compositions are identical. Moreover, since pyroxene has a rather pronounced tendency to assume its stout prismatic habit, crystallization of the unique lath shape with no lateral bulging apart of the planes of schistosity is unlikely. The more probable mode of origin is thought to be plastic deformation of originally prismatic enstatite phenocrysts.

A study of the crystal structure of enstatite reveals that layers of silica tetrahedra chains separated by layers of Mg^{++} and Fe^{++} ions are parallel to the face (100), and that the chains of silica tetrahedra are oriented parallel to crystallographic c. In such a structure, gliding would probably take place most easily in a plane parallel to the layers and in a direction parallel to the chains. The field evidence is in full accordance with this manner of gliding.

Let us postulate a "protodunite" containing a few per cent of randomly oriented prismatic pyroxene grains. Imposition of intense shearing forces on the dunite results in the mylonitization of the olivine and fracturing and bending of many of the enstatites, which are stronger than the associated olivine grains. Some of the pyroxene grains, however, namely those which have a primary orientation subparallel to that

of the resulting laths, respond not by rupturing and bending but by intragrain translation gliding parallel to the face (100). Perhaps the primary orientation deviated as much as 20° to 30° from the resulting lath orientation. If so, the orientation was accomplished probably by rotation of the stout pyroxene grains in the mobile olivine matrix rather than by more complex intragrain translation and rotation. Continued translation gliding parallel to (100) resulted in the present elongated laths. It has been pointed out that the volumes of the individual laths are of the same order of magnitude as the volumes of individual stout prisms.

It is doubtful if diopsidic lamellae could have persisted through this period of deformation. Usually during recrystallization, the diopsidic material separates into discrete grains. The fact that the laths do contain lamellae indicates that the orientation and plastic deformation of the enstatites took place before most of the lamellae were exsolved. Deformation in the 800° to 1000°C. temperature range is thus indicated. It follows that the enstatite laths formed during or soon after emplacement of the dunite.

Because the deformation of the enstatites as outlined could not take place if they were suspended in fluid, the conclusion that they were formed during or soon after emplacement indicates that this particular dunite was largely crystalline at the time of final emplacement.

As pointed out, a lineation in the northwest quadrant is imparted by the parallelism of the enstatite laths. The problem arises as to whether this lineation is parallel to or normal to the local movement direction. It will be recalled that the laths have lengths averaging 10 times the mean dimension of equant enstatites in the same hand specimen. Deformations of this order of magnitude are known only in conglomeratic pebbles aligned parallel to the movement direction (Kvale, 1948; Anderson, 1948; Fairbairn, 1949). Elongation parallel to the tectonic b-axis (usually normal to the movement direction) is thought to result from grain rotation about b such that elongation of some grain diameter in a direction normal to b is inhibited and a minor b-lengthening enhanced (Sander, 1930). According to E. Cloos (1947) this sort of elongation is nowhere pronounced. In any case this mechanism could hardly apply to single crystals 10 times as broad as they are thick, because grains of this shape cannot rotate without disintegrating. It is concluded that parallelism of the most probable glide line in enstatite with an axis of extreme stretching is strong evidence in favor of a hypothesis associating this lineation with the local movement direction.

Why a majority of the laths are subparallel to the mineral lineation in the country rock to the south and southwest is poorly understood. Because most foliation planes in the country rocks dip steeply northeast or southwest, the northwest-trending country-rock lineation must almost certainly be attributed to a northeast-southwest compression and thus be normal to the regional movement direction. The indication by the pyroxene laths that the local movement direction within the peridotite is normal to the regional movement direction can be explained either by postulating a different regional stress orientation during the peridotite emplacement or by assuming that the peridotite was emplaced in a subhorizontal direction normal to the regional compression, which locally was the direction of least stress. The latter explanation is preferred.

Summary Interpretation

During the emplacement of the Tinaquillo peridotite, either from the northwest or southeast, the green hornblende-quartz-oligoclase gneiss country rock was contact-metamorphosed to garnet-brown hornblende-augite-andesine gneiss along the south contact. At the same time, tabular masses of country rock incorporated by the peridotite were contact-metamorphosed to rocks resembling hypersthene gabbros, containing, in places, large lamellar augite and hypersthene porphyroblasts. The metamorphism involved concentration of CaO, MgO, and, to a lesser extent, FeO in the inner parts of the aureole. Relationships in the pyroxene and garnet groups indicate that the temperature of the peridotite at the time of intrusion was probably between 800° and 1000°C.

During emplacement of the peridotite, probably as a mass of crystals plus vapor, some of the enstatite phenocrysts were stretched out into long laths flattened in the planes of schistosity and elongated in the northwest quadrant, the local movement direction.

A few very thin pyroxene layers were

formed parallel to the foliation, either by mechanical segregation during intrusion or by hydrothermal alteration of dunite shortly afterward. As the intrusive mass cooled, high-temperature hydrothermal solutions moved along some of these planes, causing the alteration of pyroxene to hornblende. Below 500°C., a very small amount of serpentinization took place in the body of the dunite.

Later, northwest-directed forces caused intense low-temperature crushing of the area and thrusting along the Manrique thrust fault. The main belt of serpentinite and asbestos is tentatively attributed to alteration of the dunite by warm hydrothermal solutions circulating in the fault zone.

Age of the Tinaquillo Peridotite

No direct age determination of the Tinaquillo peridotite can be made. On the assumption that it is the same age or at least as old as the serpentinites in the coast range along strike to the east, a minimum age can be designated. Detrital chromite was found by Hess in the dated Coniacian (Upper Cretaceous) graywackes of the Arrayanes formation (Mencher *et al.*, 1953) east of San Juan de los Morros. Since the chromite can have come only from the serpentinites to the north, the serpentinites are Coniacian or older.

For reasons outlined hereafter, it is difficult to make a more specific age determination for this or any other belt of serpentinites. For the Venezuelan intrusions, the only additional clue to age is based on the following reasoning: because the serpentinite masses are structurally concordant with and occur in a belt parallel to rocks deposited and metamorphosed in late Cretaceous time, and because there is no evidence for a pre-middle Cretaceous orogenic belt having the same orientation, the serpentinites too are probably middle or late Cretaceous.

Relationship of Peridotites to Mountain Building

The fact that the Tinaquillo peridotite has a contact aureole emphasizes the need for an explanation of the absence of a contact aureole and some other peculiarities associated with most other peridotites. One such peculiarity is the conflicting age relationships serpentinites not uncommonly show toward the country rocks. Leech (1953), for example, describes a serpentinite in west-central British Columbia which has penetrated Jurassic sediments containing chromite grains derived from the peridotite itself.

In the writer's opinion, these peculiarities can possibly be explained by a hypothesis of reintrusion. Peridotites are commonly intruded into the axial zones of compressional fold mountains which commonly are subjected to continuous or repeated compression. In addition, a majority of these peridotites are serpentinites, which are weak rocks capable of being plastically deformed easily, particularly where they are brecciated and slickensided throughout. During deformations subsequent to the one in which they are emplaced (whether as a liquid or solid intrusion) serpentinites can and do move upward into younger rocks. The brecciation in the border zones of many of them attests to the faulted nature of their contacts. If, during the upward movement of a serpentinite, it is exposed to erosion, it may later be "intruded" into sediments containing its own debris. Determination of the age of a group of serpentinites subjected to differential upward movement is obviously very difficult.

In a belt of peridotites, the more serpentinized members, as mentioned, would tend to move upward and away from the site of original emplacement and hence away from any contact-metamorphic aureole. The less serpentinized and therefore more competent members would be less likely to move. The Tinaquillo peridotite, with its high-temperature contact zone, has obviously moved little from its site of emplacement.

This hypothesis of secondary and tertiary "intrusion", however, is at best only a partial explanation of the absence of contact metamorphism about peridotites, particularly the relatively unserpentinized dunites and pyroxenites such as those of North Carolina (Pratt and Lewis, 1905). Where there are peripheral talc-anthophyllite zones resulting from later hydrothermal activity, H. H. Hess (Oral communication) suggests that any contact metamorphism originally present may be masked or obliterated. Where they are very small, perhaps they simply had insufficient heat content to produce any contact effects.

Further speculation involves consideration of the physical state of primary peridotite intrusions. This falls outside the scope of the present paper.

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The Ohio Oil Company, Denver Research Center, P.O. Box 269, Littleton, Colorado

Manuscript Received by the Secretary of the Society, July 8, 1958
Princeton Investigations of Caribbean Geology, No. 10

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 71, PP. 319-362, 8 FIGS., 6 PLS. MARCH 1960

GEOLOGY OF THE MAYAGÜEZ AREA, PUERTO RICO

BY PETER H. MATTSON

ABSTRACT

The Mayagüez area forms the southwestern corner of Puerto Rico, west of 67° W. and south of 18° 15′ N. One-third of the 640 square kms is covered by thick alluvium. Unconformities separate a basal complex, two sequences of highly folded igneous and sedimentary rocks, and a younger sequence of gently dipping sedimentary rock.

The basal Bermeja complex contains serpentinite, silicified porphyritic volcanic rock with some sedimentary rock, and minor spilite, amphibolitized spilite, and amphibolite. It is exposed chiefly in some anticlinal cores in southwestern Puerto Rico.

Limestone, mudstone, andesite, and basalt form the older folded sequence. The Río Loco formation, bronzite andesite porphyry in part with pillow structures, was extruded perhaps in the Cenomanian. The Mayagüez group includes most of the rocks in southwestern Puerto Rico: the Yauco mudstone, Parguera limestone, Brujo limestone, Melones limestone, Maricao basalt, Sabana Grande andesite, and El Rayo volcanic rocks. The maximum possible age range is Turonian to Maestrichtian. The group ranges in thickness from about 800 m in the south to 3800 m in the north, and it varies in lithology from limestone in the south to mudstone and volcanic rock in the north, indicating a volcanic center to the north during that time.

The second folded sequence contains andesitic volcanic rock, bedded tuff, and massive limestone. The San Germán formation (Maestrichtian) includes andesite, the Cabo Rojo agglomerate member, and the Cotui limestone member. The Jicara formation, massive limestone and bedded tuff, is Paleocene; there is one exposure of an unnamed ?Eocene marl.

Post-Eocene limestone and conglomerate are also exposed in the area.

The structure of the basement complex is obscured by its massiveness and by the cover of younger rocks. Two major deformations have affected the rocks of southwestern Puerto Rico since Cenomanian to Santonian time. In the Maestrichtian, the first of these formed folds with a N. 60° W. trend, asymmetric or overturned to the south. Near the south coast the folding of thin Mayagüez group rocks was probably influenced by trends in the Bermeja complex which caused deviations in the regional trends and also some overturning to the north.

The San Germán formation, deposited unconformably on the eroded surface of the folded Mayagüez group, contains large allochthonous blocks of older and contemporaneous rocks. These blocks, up to 2 km by 1 km in exposure, were deposited by slumping or sliding due to gravity within and at the base and top of the San Germán formation near Lajas and San Germán. Most rocks in the blocks are extremely contorted and contain deformed Foraminifera. The San Germán and Jicara formations and perhaps the ?Eocene marls were deformed into gentle open folds trending east in the area covered by this report. Oligocene, Miocene, and younger sedimentary rocks have been tilted and uplifted.

Large east-west left-lateral transcurrent faults cross the area, offsetting and offset by two sets of transverse faults (N. 45° E., N. 20° W.): most faults are probably Maestrichtian to Oligocene, although minor faulting has continued to the present.

Dikes and sills of quartz diorite porphyry and mica-quartz dacite porphyry intrude the ?Maestrichtian San Germán formation and older units. A diorite plug cuts the Bermeja complex, and a granodiorite plug intrudes the Mayagüez group.

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Introduction and Acknowledgments

The paper represents one of a group of field investigations being sponsored by Princeton University in the eastern Caribbean (Hess and Maxwell, 1953) and was submitted in partial fulfillment of the requirements for the Ph.D. at Princeton University. Thirteen months of field work were completed during 1953–1956; laboratory investigations were carried out at Princeton University. The project was financed by the Economic Development Administration, Commonwealth of Puerto Rico and also by the Higgens Fund, Department of Geology, Princeton University, and the Office of Naval Research contract N6onr-27008.

The author greatly appreciates the assistance and encouragement of Prof. H. H. Hess, who suggested this project and aided its completion in every way. The following also aided and encouraged the work: A. G. Fischer, A. F. Buddington, and F. B. van Houten of Princeton University; R. Fernandez García and Mort D. Turner of the Department of Industrial Research, Commonwealth of Puerto Rico; Don Luis Stefani and John D. Weaver of the University of Puerto Rico; and Watson Monroe, R. J. Smith, and J. B. Owens of the U. S. Geological Survey. G. Gross, E. A. Pessagno, Jr., and G. Otálora gave excellent field assistance. R. J. Smith and C. A. Kaye reviewed the manuscript and offered many helpful suggestions pertaining to organization and content of the paper.

The author is indebted to Dr. Paul Bronnimann, who examined more than a hundred limestones and mudstones and identified and dated the microfauna. The age determinations were critical to the understanding of stratigraphic relationships in this area of abruptly changing lithofacies. E. A. Pessagno, Jr., studied the free microfauna and gave much advice on the use of the paleontological

data. Other fossils were identified by L. J. Chubb (rudists), W. Storrs Cole (benthonic Foraminifera), H. Bolli (pelagic Foraminifera), N. F. Sohl (gastropods), D. Nicol (pelecypods), C. W. Cooke (echinoids), and J. B. Reeside (inoceramids); these contributions are gratefully acknowledged.

Nomenclature

The nomenclature used in this report is, in general, that of Williams, Turner, and Gilbert (1954). Ages of the rock units are tentative and are based upon limited paleontological information derived largely from the study of Foraminifera and rudists, interpreted in the light of structural evidence. Ages are generally given in terms of the extreme possible limits, *e.g.*, Turonian to Campanian, and do not necessarily imply that the formation extends throughout the interval.

Previous Work

G. J. Mitchell (1922) and Hubbard (1923) prepared reconnaissance reports on western Puerto Rico. Zapp, Bergquist, and Thomas (1948) have described post-Eocene rocks of the coastal plain, and McGuinness (1948) discussed ground-water problems. Good general surveys of the geology of Puerto Rico are by Berkey (1915) and Meyerhoff (1933). This report emphasizes the pre-Oligocene sedimentary and igneous rocks.

Geography

Puerto Rico lies north of the Caribbean Sea, between Hispaniola on the west and the Virgin Islands on the east. The Mayagüez area includes the six 7½-minute quadrangles forming the southwest corner of the island, an area of 640 square kms, of which 215 square kms is covered with alluvium (Fig. 1).

The climate is tropical. Rainfall ranges from 30 inches on the south coast to about 100 inches in the northeast corner of the Mayagüez area. Extreme evaporation causes the south coast to have a semiarid climate. The northeast trade winds prevail, so most of the rain falls on the north side of the island.

Geomorphology

Southwestern Puerto Rico is maturely dissected, cut by two large alluvium-filled valleys and modified by coastal processes. The two large valleys, the Valle de Lajas and the Valle de Guanajibo, trend east and are bounded in part by faults. Drainage is funneled to the coast either directly or via the large valleys. The larger rivers meander in moderate-sized flood plains. The southern drainage is poorly integrated because of the lack of rainfall; much of the Valle de Lajas has interior drainage.

The northern and southern parts of the region differ, mainly owing to the decrease in rainfall from north to south. Knife-edged ridges with slopes up to 30°–45° are formed in the north in clayey soils, with erosion generally by sheet wash and slump during torrential rains, although gullies once begun enlarge rapidly. Saprolites are common. In the drier south, the rolling hills are broken only by limestone cliffs, with more rocky and limy soils.

The Valle de Guanajibo is essentially an anticline breached by erosion. Lobeck (1922, p. 312) thinks that the Valle de Lajas is also a breached anticline; T. R. Slodowski (1956, unpub. Ph.D. thesis, Princeton Univ., p. 4) believes that it is synclinal, underlain by Paleocene sediments. Detailed mapping north and south of the valley shows that there is no such simple relationship to structure (Figs. 4, 5; Pl. 1). A Paleocene syncline does underlie part of the eastern part of the valley, but it crosses the valley diagonally and is north of the valley in the Mayagüez area. Other structures also cross the valley diagonally.

Lobeck (1922, p. 318 *et seq.*) has suggested that the Oligocene-Miocene rocks were deposited on a surface of some relief, preserved in the Valle de Lajas to the present day, at least in the areas of Oligocene-Miocene outcrop in the valley. Downfaulting of the Valle de Lajas with erosion of corresponding younger sediments from the bordering highlands could also explain the field data (Kaye, 1957); evidence of faulting exists along the borders of the Valle de Lajas (Pl. 1).

Stratigraphy

General Statement

The oldest rocks in the Mayagüez area are in the basal or Bermeja complex. They include silicified volcanic rock, spilite, amphibolite, and serpentinized peridotite.

A broadly folded sequence of sedimentary and volcanic rocks, of Cenomanian or Santonian to Paleocene or possibly Eocene age,

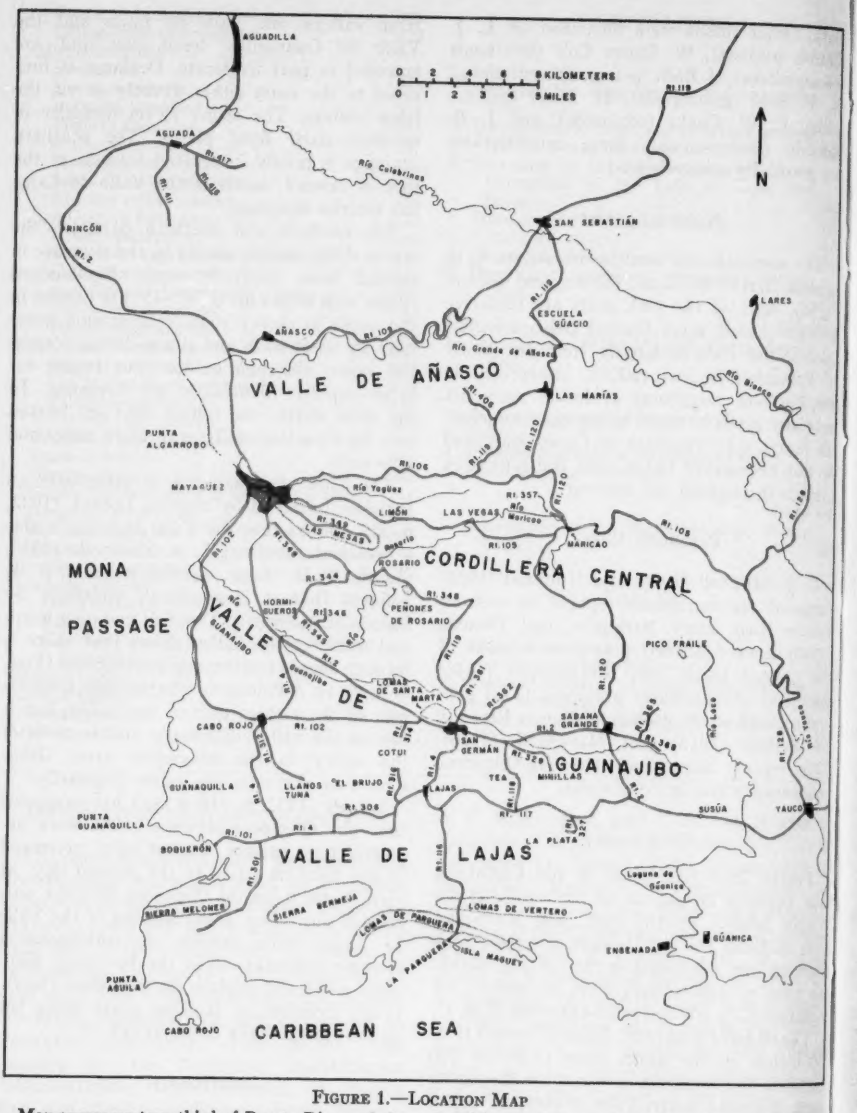

FIGURE 1.—LOCATION MAP

Map covers western third of Puerto Rico and shows localities, highways, and topographic features mentioned in the text.

unconformably overlies the complex, in some places with a basal conglomerate (Fig. 2). This sequence is subdivided by an unconformity (Maestrichtian). Below the unconformity are the Río Loco formation and the Mayagüez group, and above the unconformity are the San Germán and Jicara formations and a small exposure of ?Eocene.

A younger tilted and uplifted sequence includes Oligocene-Miocene limestones, gravels, and clays, Miocene limestone and clays, and Pleistocene dune sands. These are the

Juana Díaz, Ponce, Guanajibo, and San Juan formations.

Bermeja Complex

Rock types.—The oldest rocks in southwestern Puerto Rico form the Bermeja complex, which is exposed in greatest variety in the Sierra Bermeja. The Bermeja complex occurs chiefly in the centers of most anticlines in southwestern Puerto Rico. Hubbard (1923, p. 14–15) mentioned exposures of lateritic soil south of Aguada that he correlated with the serpentinite, but this author could not locate them; they may be merely red volcanic soils. The complex is composed mainly of serpentinized peridotite, now serpentinite, with spilite, amphibolite, and minor silicified volcanic rock and/or chert. White fine-grained inclusions up to 2 m in diameter in the serpentinite in several places, notably in the outcrops north and east of San Germán, are largely composed of grossularite.

SERPENTINITE: The serpentinite is an intensely sheared green, greenish-white, bluish-green, or brownish-black rock, in some cases with visible green pyroxene crystals. Serpentinite is well exposed on routes 118 and 349, on routes 119, 347, and 362 near San Germán, on Lomas de Santa Marta immediately northwest of San Germán in the Valle de Guanajibo, and on Route 120 in the Yauco area.

Thin sections show partial or complete alteration to serpentine minerals. Unaltered cores of grains show that the original minerals were colorless and nonpleochroic enstatite and forsterite. Minor minerals are chromite and ore. No clinopyroxene or feldspar were seen.

Serpentinite microbreccia is found near faults on the north and south sides of the Hormigueros syncline (Pl. 2, fig. 1), and serpentinite containing

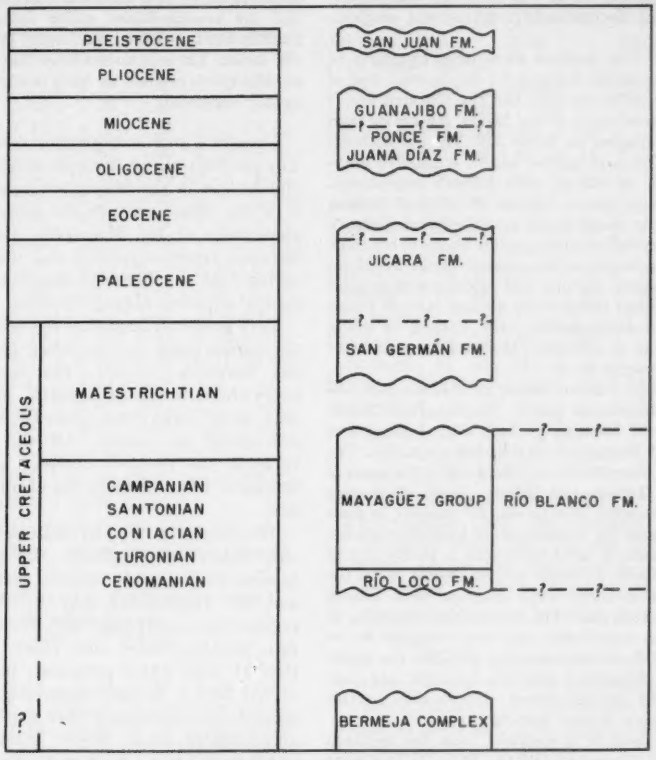

FIGURE 2.—STRATIGRAPHIC SEQUENCE FOR THE MAYAGÜEZ AREA

Wavy lines show unconformities. The position of the Río Blanco formation, found only in the northern part of the area, is uncertain.

introduced calcite and silica occurs along a fault paralleling the south side of Sierra Bermeja.

SILICIFIED VOLCANIC AND SEDIMENTARY ROCK: Most of the Sierra Bermeja is composed of a black or greenish-gray siliceous rock that weathers reddish. It is massive and intensely brecciated; bedding is rare. Thin sections show that most of the unit is cryptocrystalline silica, but there are some specimens of silicified volcanic porphyry and conglomerate.

SPILITE: Two quarries show large exposures of spilite. The northern one is 1.1 km by road east of Mayagüez on Route 105, and the southern one is on a side road south of Las Mesas, 0.6 km by road east of Mayagüez on Route 349. The northern exposure consists of spilitic basalt, a massive gray-green rock in contact with foliated serpentinite. The southern quarry exposes fine-grained diabase or gabbro, in places partly amphibolitized. Veins of coarsely crystalline anthophyllite up to 10 cm thick extend the length of the quarry, about 10–15 m. Smaller quartz, epidote, and calcite veins are also seen. A coarser facies of the diabase in some places borders the anthophyllite veins. Diabase or spilite is also found as pebbles in the basal conglomerates of the Mayagüez group.

The spilite is about 60 per cent albite laths, 20 per cent interstitial augite ($Ca_{41}Mg_{50}Fe_9$), 15 per cent chloritic material (perhaps altered glass), and 5 per cent ilmenite or titaniferous magnetite. The texture is intergranular or intersertal in the sense of Williams, Turner, and Gilbert (1954). Plagioclase occurs in twinned crystals usually unzoned, in some cases replaced by prehnite or by hydrogrossularite. The pyroxene in some specimens is partly altered to hornblende. In these amphibolitized rocks the plagioclase is zoned sodic andesine with altered cores and fresh rims. The hornblende is identical to that of the amphibolite described hereafter: Nz = 1.666, 1.670; extinction angle, 18°–20°; the augite in one amphibolitized sample is 5 mol per cent more calcic. The amphibolitized spilites also contain minor epidote, sphene, and chlorite.

The analysis of a specimen from the northern quarry at Mayagüez (PR42, Table 1) is similar to that of spilite. The Puerto Rican specimen less MgO and TiO_2 and more Al_2O_3 than the average spilite.

AMPHIBOLITE: Amphibolite occurs in the Bermeja complex as inclusions and possibly as lenses in the serpentinite in the Sierra Melones, the Sierra Bermeja, and much less commonly in the northern outcrops. Some rock exposures show a lineation. The rock is composed of equal amounts of green hornblende and plagioclase, both granoblastic and about 0.1–1.0 mm. Magnetite is a common accessory mineral. The plagioclase is calcic andesine or labradorite. Pyroxene remnants in the centers of the amphiboles are rare. Some cores of the plagioclase are partly sericitized, but most of the rims are fresh. Twinning is rare, but zoning is common in the plagioclase.

Table 1 gives the chemical analysis of an amphibolite (PR336) from the eastern Sierra Melones. It is similar to an olivine basalt. The analyzed specimen is more fine-grained than other specimens (0.1–0.2 mm); it is near a fault. The barium content is extraordinarily high; small barite veins are common in the area.

The degree of alteration of the feldspar and the presence of identical hornblende in the amphibolite and the amphibolitized spilite indicate that the amphibolite may have been formed by alteration of the spilite. There is no evidence that the spilite is an alteration product of more mafic rocks, as is usually suggested.

Structural and stratigraphic relationships.—The position of the Bermeja complex in anticlinal cores in the Mayagüez area shows that it is the oldest unit in the area. Basal conglomerates of the Mayagüez group contain Bermeja complex pebbles and minerals, indicating that the Bermeja complex was eroded during or before Mayagüez time.

Very little can be said of the relationships of the serpentinite to the other rock types in the Bermeja complex. The serpentinite is everywhere intensely sheared, and contacts with other rocks have often become zones of differential movement. All the other rock types in the Bermeja complex are found as blocks or fault slices in the sheared serpentinite.

The extensive silicified rocks in the complex, only finely recrystallized, are perhaps the product of low-grade regional metamorphism, and the amphibolite may be the result of regional metamorphism also. However, recent experiments (Yoder and Tilley, 1956) show that at high water pressures, basalt is converted into a mineral assemblage similar to amphibolite, indicating that perhaps primary amphibolites occur below great depths of water on the ocean floor or in oceanic deeps.

The age of the Bermeja complex is unknown, as no fossils have been found. Age determinations in the basal Mayagüez rocks resting unconformably upon the serpentinite show that the Bermeja complex is older than Santonian-Campanian and is possibly older than Cenomanian. In the Dominican Republic peridotite intrudes late Early Cretaceous or younger schists (Koschmann and Gordon, 1950).

Río Loco Formation

Rock types.—The Río Loco formation contains bronzite andesite porphyry lavas, more than half with pillow forms, and subordinate

TABLE 1.—CHEMICAL ANALYSES OF IGNEOUS ROCKS FROM SOUTHWEST PUERTO RICO
In weight per cent. Analysts: D. Thaemlitz (PR7, 29, 42, 66), C. O. Ingamells (PR336), Rock Analysis Laboratory, University of Minnesota

Specimen number	PR42	PR336	PR7	PR66	PR29
SiO_2	51.69	46.03	49.73	53.00	60.79
Al_2O_3	15.50	14.40	14.98	17.50	18.80
Fe_2O_3	2.46	2.08	3.89	3.21	0.95
FeO	7.10	8.11	5.38	3.52	2.05
MgO	6.72	10.86	7.06	2.52	1.92
CaO	6.03	10.32	8.24	8.79	4.40
Na_2O	5.06	1.94	2.86	3.75	4.30
K_2O	0.75	0.34	2.87	0.65	1.91
H_2O+	2.69	3.24	2.45	1.91	2.02
H_2O-	0.16	0.20	0.59	0.29	0.37
CO_2	0.12	n.d.	0.14	3.31	1.75
TiO_2	1.21	1.33	1.07	0.76	0.30
P_2O_5	0.10	0.10	0.29	0.38	0.17
MnO	0.17	0.21	0.16	0.12	0.09
BaO	n.d.	0.45	n.d.	n.d.	n.d.
S	n.d.	0.01	n.d.	n.d.	n.d.
Cl	n.d.	0.04	n.d.	n.d.	n.d.
	99.76	99.66	99.71	99.71	99.82
(less O for Cl and S)		0.01			
Total	99.76	99.65	99.71	99.71	99.82

Normative Minerals of Analyzed Specimens (in weight per cent)

Quartz	.....	.....	.....	15.24	20.46
Orthoclase	4.45	2.23	16.68	3.34	11.13
Albite	42.97	16.25	24.10	31.96	36.16
Anorthite	17.24	29.45	19.74	20.00	9.74
Corundum	.....	.....	.....	3.37	6.22
Diopside	9.71	17.45	15.76	.....	.....
Hypersthene	3.16	10.57	3.19	8.94	7.31
Olivine	13.19	14.08	8.65	.....	.....
Magnetite	3.71	3.01	5.57	4.74	1.39
Ilmenite	2.28	2.58	1.98	1.52	0.61
Apatite	.....	0.34	0.67	1.01	0.34
Calcite	0.20	.....	0.30	7.50	4.00
Water	2.85	3.40	3.04	2.20	2.39
Total	99.76	99.40	99.68	99.82	99.75

TABLE 1.—*Continued*

Specimen number	PR42	PR336	PR7	PR66	PR29
Feldspar* by norm	Or 5	3	21	4	16
	Ab 54	22	31	44	56
	An 41	75	48	52	28
Feldspar by index oils	Ab 90–100	35–45	.....	48–63	66
	An 0–10	55–65	.....	37–52	34
Diopside* by norm	Wo 50	50	50	.....	.....
	En 35	38	32	.....	.....
	Fs 15	12	18	.....	.....
Augite* by optics	Ca 41	.....	43	.....	.....
	Mg 50	.....	36	.....	.....
	Fe 9	.....	21	.....	.....
Hypersthene* by norm	En 72	75	80	76	72
	Fs 28	25	20	24	28
Olivine* by norm	Fo 70	76	82	.....	.....
	Fa 30	24	18	.....	.....
CIPW classification	II535	III545	II435	II534	II224

* Molecular per cent

Location of specimens (*See* Plate 1):

PR42—Spilite from the Bermeja complex; quarry on Route 106 1 km east of Mayagüez

PR336—Amphibolite from the Bermeja complex; road cut on Route 301 between Sierra Melones and Sierra Bermeja, on south edge of Valle de Lajas

PR7—Trachybasalt from the Maricao basalt, about 1.5 km south of Río Yauco dam, on Route 128 north of Yauco in the Yauco area (T. R. Slodowski, 1956, unpub. Ph.D. thesis, Princeton Univ., p. 110a-b)

PR66—Pyroxene andesite porphyry from Sabana Grande andesite, 0.8 km west of Route 118 on a path from km 1.4; southeast of San Germán

PR29—Quartz diorite porphyry; intrusive; km 0.7, Route 118, southeast of San Germán

tuff, breccia, hornblende andesite, dacite (?), and limestone. Named by T. R. Slodowski (1956, unpub. Ph.D. thesis, Princeton Univ., p. 53) from its exposures on the Río Loco in the Yauco area, it is redefined herein to include the bronzite andesite near Parguera and Guanica and to exclude a large fairly continuous mudstone unit considered Yauco mudstone. The best outcrops in the Mayagüez area are on the east-west unpaved road from Mayagüez between routes 348 and 349 in the valley of the Quebrada Grande. Small outcrops north of Cabo Rojo are tentatively correlated with the formation. In the northern

exposures the formation is approximately 300 m thick; no thicknesses could be measured elsewhere.

The Río Loco basaltic (bronzite) andesites are porphyritic rocks containing pyroxene and plagioclase (labradorite-bytownite) phenocrysts in a brown or blue-black aphanitic matrix. Two types of pyroxene can be distinguished on a fresh surface: equidimensional diopsidic augite crystals and lath-shaped waxy green crystals of partially serpentinized bronzite. Pillow structures are common in the northern outcrop area and absent in the southern area. The pillows are outlined by a facies of the porphyry with spherules of silica and chlorite in a light-colored, probably silicified, matrix. Veins of quartz are common. The pillows average 1 m in diameter and have no marked dimensional orientation. Interstices are filled with quartz, chert, or finely recrystallized limestone. The rocks weather to a coarse sand, and spheroidal weathering is common.

TABLE 2.—CHEMICAL ANALYSES OF ROCKS FROM THE RÍO LOCO FORMATION

In weight per cent. Analysts: D. Thaemlitz (PR 26, 672, 786), C. O. Ingamells (PR 2509, 2526, 2766), Rock Analysis Laboratory, University of Minnesota

Specimen number	PR786	PR2766	PR672	PR2509	PR2526	PR26
SiO_2	55.55	55.11	54.70	57.06	56.25	59.28
Al_2O_3	12.18	13.27	18.03	16.78	15.38	12.12
Fe_2O_3	2.70	3.07	3.14	2.62	2.36	1.55
FeO	6.03	4.93	4.84	3.96	5.13	5.64
MgO	9.10	7.17	3.81	3.41	4.61	7.00
CaO	7.25	7.25	8.96	8.59	10.00	5.74
Na_2O	2.15	2.45	2.48	2.78	2.06	3.11
K_2O	1.66	2.35	0.38	0.50	0.34	0.92
H_2O^+	0.94	2.14	1.65	2.27	2.18	2.50
H_2O^-	0.89	0.55	0.36	0.48	0.36	0.43
CO_2	0.03	0.16	0.02	n.d.	n.d.	0.05
TiO_2	0.75	0.84	0.97	0.94	0.82	0.76
P_2O_5	0.27	0.37	0.33	0.31	0.19	0.30
MnO	0.14	0.13	0.14	0.17	0.14	0.13
BaO	0.19	0.15	0.06	0.07	0.05	n.d.
S	0.03	0.01	0.01	0.00	0.00	n.d.
(Less O for S)	99.86 0.01	99.95	99.88	99.94	99.87	99.53
Total	99.85	99.95	99.88	99.94	99.87	99.53

Normative Minerals of Analyzed Specimens

(in weight per cent)

Quartz	8.58	7.62	13.80	16.45	15.79	14.40
Orthoclase	9.45	13.92	2.22	2.79	2.23	5.56
Albite	17.82	20.95	20.96	23.57	17.29	26.20
Anorthite	19.18	18.07	36.70	31.97	31.68	16.41
Diopside	12.11	11.34	4.94	7.17	13.76	7.97
Hypersthene	24.60	17.79	11.86	8.87	11.06	21.56
Magnetite	3.94	4.41	4.41	3.71	3.48	2.32
Ilmenite	1.37	1.67	1.98	1.83	1.52	1.52
Apatite	0.67	0.10	0.67	0.67	0.34	0.67
Calcite	.....	0.40	.....	.....	.....	0.10
Water	1.83	2.69	2.01	2.75	2.54	2.93
Total	99.55	98.96	99.55	99.78	99.69	99.64

TABLE 2.—*Continued*

Specimen number	PR786	PR2766	PR672	PR2509	PR2526	PR26
Feldspar* by norm	Or 20	19	4	3	3	8
	Ab 38	31	35	27	22	42
	An 42	50	61	70	75	50
Feldspar by index oils	Ab 42	39–45	29	39	41–46	53–60
	An 58	55–61	71	61	54–59	40–47
Diopside* by norm	Wo 50	50	50	50	50	50
	En 36	40	40	38	35	37
	Fs 14	10	10	12	15	13
Augite* by optics	Ca 45	46	45	42	49	37
	Mg 36	46	36	52	43	46
	Fe 19	8	19	6	8	17
Hypersthene* by norm	En 75	82	67	74	70	74
	Fs 25	18	33	26	30	26
Hypersthene* by optics	Mg 84	71	72	72	71	..
	Fe 16	29	28	28	29	..
CIPW classification	III444	II(III) 433(4)	II444–5	II445	II445	II434

* Molecular per cent

Location of specimens (*See* Plate 1):

PR786—Bronzite andesite porphyry; northeast edge of the town of Yauco (T. R. Slodowski, 1956, unpub. Ph.D. thesis, Princeton Univ., p. 110a-b)

PR2766—Bronzite andesite porphyry; 1.7 km southwest of Las Vegas, on a path on Cuchillas de Aceitunas

PR672—Feldspathic bronzite andesite porphyry; about 1.0 km south of Laguna de Guánica (*See* Fig. 4; *See also* T. R. Slodowski, 1956, unpub. Ph.D. thesis, Princeton, Univ.)

PR2509—Feldspathic bronzite andesite porphyry; about 5.0 km northeast of Parguera and 0.6 km south of Route 116

PR2526—Feldspathic bronzite andesite porphyry; about 1.1 km west-northwest of Parguera

PR26—Pyroxene andesite porphyry; about 2 km east-northeast of Sabana Grande, on Route 365 (T. R. Slodowski, 1956, unpub. Ph.D. thesis, Princeton Univ.)

BRONZITE ANDESITE PORPHYRY (BASALTIC ANDESITE) (PL. 2, FIG. 2): The groundmass of the analyzed rock specimens contains 0.005–0.06-mm microlites of plagioclase, orthopyroxene, clinopyroxene, and magnetite embedded in a turbid brown glass (?) with patches of clear silica. Amygdules of calcite, chlorite, and quartz occur in specimens other than those analyzed. Phenocrysts make up 40 per cent of this porphyritic rock; they include plagioclase (20 per cent), diopsidic augite (10 per cent), and bronzite (10 per cent). Many rock samples show a glomeroporphyritic texture. Plagioclase occurs as subhedral twinned and zoned laths averaging 1 mm long, commonly sericitized or rarely altered to calcite or epidote. Of eight determinations made, five were An_{68-61} and three were An_{71-75}, averaging An_{64}. The three samples were from plagioclase-rich rocks. Diopsidic augite occurs as fresh, subhedral, equidimensional crystals averaging 1 mm, commonly partly resorbed. Many of the augites have cores of orthopyroxene; orthopyroxene rims are rare. Orthopyroxene, generally bronzite, is found in subhedral laths averaging 0.6 mm long, partly or completely serpentinized (?bastite). The laths show colorless to pink pleochroism and have a negative optic angle of 65°–77°. Rims of augite are common, and partial rims of plagioclase are rare. The composition of five samples determined by optical methods averages 72 per cent enstatite, corresponding to bronzite (Hess and Poldervaart, 1951). Sample PR2766 has some bronzite crystals containing calcite cores, perhaps pseudomorphs after olivine. Specimen PR2487 contains a few fresh hypersthene laths with thin clinopyroxene lamellae; it also contains rare magnetite-hypersthene intergrowths, commonly surrounded by augite grains.

The northern and southern lavas are similar mineralogically and texturally. The southern lavas have a larger percentage of phenocrysts, a smaller percentage of orthopyroxene phenocrysts, and about twice as many plagioclase phenocrysts (Table 3).

Table 2 gives chemical analyses of the Río Loco lavas. The analyses are grouped as southern lavas and northern lavas and correspond to basaltic andesite, intermediate between basalt and andesite. The southern lavas correspond to ordinary basaltic andesite, and the northern lavas are, by analysis, K_2O rich basaltic andesite. The southern lavas

TABLE 3.—MODAL ANALYSES OF ROCKS FROM THE RÍO LOCO FORMATION
In volume per cent

Specimen number	Matrix	Phenocrysts	Volume per cent of:					An	En
			Opx*	Cpx	Pc	Mt	Other	(by optics)	
(South)									
672	61.2	38.8	2.7	0.9	32.2	3.0	...	71	72
2349	48.4	51.6	5.9	11.1	33.5	1.1	...	75	***
2403	51.3	48.7	4.9	19.4	24.4	...	...	60	***
2487	53.3	46.7	5.3	7.9	31.5	2.0	...	75	68
2509	60.1	39.9	2.2	6.5	27.6	3.6	...	61	72
2526	65.9	34.1	9.6	12.4	11.2	0.9	...	56	71
average:	56.7	43.3	5.1	9.7	26.8	1.9	...		
(North)									
26	71.5	28.5	15.6	5.0	7.2	...	0.7†	42	***
786	58.9	40.4	8.8	16.0	15.6	...	0.7**	58	84
2674	63.2	36.8	18.0	6.5	10.1	2.2	...	***	...
2766	60.0	40.0	9.8	9.8	20.4	...	...	58	71
2898	63.0	35.2	22.1	5.3	7.3	0.5	1.8††	***	...
2899	65.1	34.9	16.8	11.5	6.6	...	...	59	79
average:	63.6	36.4	12.5	9.0	11.2				
total average:	60.1	39.9	8.8	9.4	19.0			64	72

* Small magnetite crystals are counted as matrix in some cases; mt—magnetite, pc—plagioclase, cpx—clinopyroxene, opx—orthopyroxene

† hornblende (?)

**amygdules

††amygdules and veins

***altered

Location of specimens not given in Table 2 (*See* Plate 1):

PR2349—Feldspathic bronzite andesite porphyry; about 5.5 km west-northwest of Parguera, south of Sierra Bermeja

PR2403—Feldspathic pyroxene andesite porphyry; small outcrop in central Sierra Melones, in Parguera limestone

PR2487—Felspathic hypersthene andesite porphyry; about 2 km north of Parguera, 250 m east of Route 304; specimen contains several hypersthene laths with clinopyroxene exsolution lamellae

PR2674—Pyroxene andesite porphyry; about 6.0 km northeast of San Germán, 250 m east of the border of the area

PR2898—Pyroxene andesite porphyry; about 7.2 km north of San Germán, near intersection of routes 348 and 119

PR2899—Bronzite andesite porphyry; about 2.3 km southeast of the center of Mayagüez, on a dirt road running along the Río Loco formation outcrop

average 3.9 per cent MgO, similar to andesite, whereas the northern lavas average 8.1 per cent MgO, similar to basalt. Analyses of the northern lavas show similarities to the analysis of the Maricao trachybasalt in the high K_2O and low alumina content, but the northern lavas have much more silica.

There are minor amounts of augite andesite porphyry and hornblende andesite porphyry in the southern Río Loco exposures. A more siliceous specimen from the Yauco area is a hornblende dacite porphyry by analysis (T. R. Slodowski, 1956, unpub. Ph.D. thesis, Princeton Univ., p. 110a).

Contact relationships and age.—The Río Loco formation occurs on the flanks of the

Las Mesas-Fraile anticline and in the southeastern part of the area. It lies between the Mayagüez group and the Bermeja complex. Bedding in the Mayagüez group, parallel to the contact of the Mayagüez and the Río Loco formation, is in most places parallel to sedimentary lenses within the Río Loco. No fossils have been found in the unit in southwest Puerto Rico. In eastern Puerto Rico, near Coamo, shales associated with pillow lavas correlated with the Río Loco lavas have been dated as Cenomanian by Paul Brönnimann (E. A. Pessagno, Jr., personal communication).

Depositional environment.—Pillow structures and interbedded mudstones and siltstones indicate a submarine environment for the northern lavas. The occurrence of only one sedimentary lens in the southern lavas, the absence of pillow structures, and the presence of a silicified soil (?) zone at the coast in the Sierra Melones occupying the same stratigraphic interval all imply that the southern lavas were formed in part subaerially.

Mayagüez Group

Structures.—The Mayagüez group, named for the Mayagüez map area, comprises most of the rocks in southwestern Puerto Rico. The group is composed of bedded and massive fragmental limestone; thin- to medium-bedded foraminiferal tuffaceous mudstone, siltstone, and tuff; and andesitic and basaltic volcanic rock including massive tuff, lava, and breccia. It is about 780 m thick near the south and southwest coasts and up to 3800 m thick near the northeastern corner of the area, 28 km to the north. The group rests conformably upon the Río Loco formation and, where the Río Loco is absent, with clear-cut unconformity upon the Bermeja complex. The youngest rocks in the Mayagüez group are Maestrichtian; the oldest are in the Turonian to Santonian range.

The Mayagüez group comprises seven lithofacies units of formational rank. These are the Parguera, Brujo, and Melones limestones, the Yauco mudstone, the Maricao basalt, the Sabana Grande andesite, and the El Rayo volcanic rocks. In this classification the Mayagüez group and the Melones limestone are lithologic units which correspond to time-stratigraphic units within the Mayagüez area, whereas the six other formations are regarded as lithologic units or lithofacies, with no implications of position relative to one another. The relationships within the Mayagüez area are shown in Figure 3.

Within the area, thick tuffaceous mudstone grades southward into limestone and calcareous mudstone, with both lithologies occurring in the central regions. Basaltic volcanic rock is predominant in the north and extends southward in minor amounts, and andesitic volcanic rock is most common in the central portion of the map area.

It must be emphasized that the units within the Mayagüez group are lithofacies; their relative positions may vary laterally (with the possible exception of the Melones limestone).

The units occur in four major structural regions (Fig. 5): (1) the Las Vegas syncline; (2) the Hormigueros syncline; (3) the Tea syncline and the Brujo structure; and (4) the Parguera anticline and the Melones and Vertero synclines. The lithologic similarities and differences from place to place and the variation in proportions of the units within the Mayagüez group are described hereafter. (*See also* Figure 3.) The vertical and lateral variation within short distances is characteristic of a volcanic terrain in a marine or locally nonmarine environment.

LAS VEGAS SYNCLINE: The Las Vegas syncline is the northernmost fold in the Mayagüez area, extending from the northern serpentinite body about 9 km northward to the contact of the Mayagüez and Río Blanco units. The Mayagüez group rests conformably on the Río Loco formation in the south limb of the fold and is in fault contact (?) with the Río Blanco formation in the north limb.

The Mayagüez group in the Las Vegas syncline includes the Yauco mudstone and the Maricao basalt. The basalt occurs above and as lenses in the mudstone in the Las Vegas syncline and also to a limited extent in the south in the Hormigueros syncline. The lenses average 600 m total thickness in each limb of the Las Vegas syncline, and the upper basalt unit has a minimum thickness of 800 m. The mudstone averages 2400 m thick in the south limb of the syncline and 2800 m in the north limb.

Age determinations in the Las Vegas syncline are all from the Yauco mudstone; they range from Maestrichtian in the center to Turonian to Campanian, perhaps Campanian at the base of the southern limb.

HORMIGUEROS SYNCLINE: The mudstone lithofacies from the north and the limestone lithofacies from the south interfinger within the Hormigueros syncline in the north-central part of the area and the Tea syncline in the east-central part (Fig. 3; Pl. 1). The Río Loco formation and the Maricao basalt occur on the north limb of the Hormigueros syncline, and lenses of Sabana Grande andesite are within the Parguera limestone near the center of the same syncline.

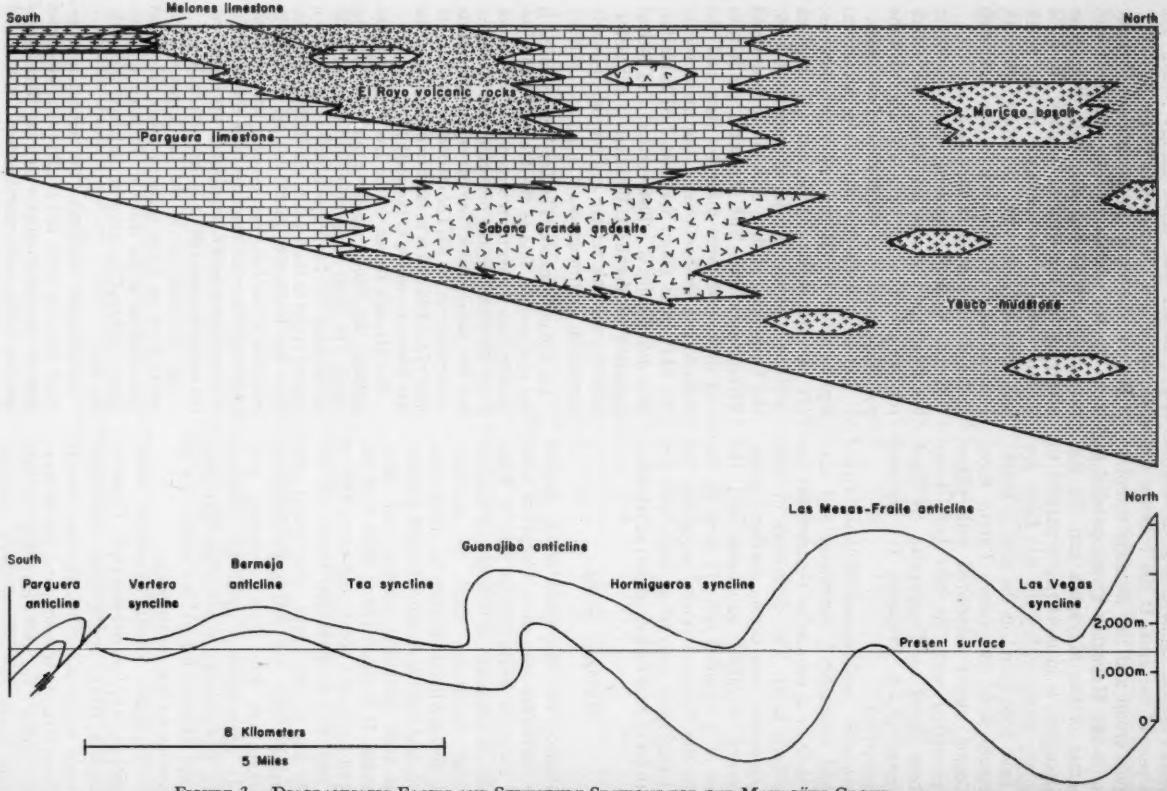

FIGURE 3.—DIAGRAMMATIC FACIES AND STRUCTURE SECTIONS FOR THE MAYAGÜEZ GROUP

In the eastern half of the area the mudstone lithology occurs above the Sabana Grande andesite as far south as the Tea syncline. The Brujo limestone is mapped as Parguera limestone.

The Hormigueros syncline, 7–8 km wide, strikes N. 60°W. and extends beyond the eastern boundary of the area along the strike. Strata in the syncline total about 2750 m, consisting of maximum thicknesses of 250 m of Yauco mudstone, 1300–1400 m of Sabana Grande andesite, and 300–400 m of Maricao basalt, and a minimum thickness of 700 m of Parguera limestone. Fossils have been found only in the Yauco and Parguera units; the youngest assemblages in the center of the syncline are early Maestrichtian, and assemblages from the basal beds of the Mayagüez group are Turonian to Campanian.

TEA SYNCLINE AND THE BRUJO STRUCTURE: The sedimentary rocks in the Tea syncline are divided into three lenses or tongues by thick volcanic rocks. From bottom to top the units are: Yauco mudstone (200 m), Sabana Grande andesite (475 m), Yauco mudstone (400 m), El Rayo volcanic rocks (1000 m), and Melones limestone (15–100 m) (Fig. 3). Lenses of the Melones limestone occur within the El Rayo volcanic rocks, and the Brujo limestone is the equivalent of the upper tongue of Yauco mudstone in the western part of the syncline.

The northern limb of the Tea syncline is well exposed between San Germán and the eastern border of the area, especially on Route 118. To the west the syncline is covered by younger volcanic and sedimentary rocks of the San Germán formation; the southern limb of the syncline is covered by alluvium.

The center of the Tea syncline at the edge of the Valle de Lajas is dated as Maestrichtian; the only other age determinations are Turonian to Campanian and middle Campanian, in the upper tongue of the Yauco mudstone.

PARGUERA-VERTERO-MELONES STRUCTURES: The Parguera anticline, the Vertero syncline, and the Melones syncline, composed predominantly of Parguera limestone with minor amounts of Melones limestone and Río Loco lava, form the southern part of the Mayagüez area. The Parguera limestone ranges from Santonian, perhaps Turonian, to Maestrichtian, and averages 780 m in thickness. The Melones limestone is Maestrichtian and has a minimum thickness of 175 m.

FIGURE 3.—DIAGRAMMATIC FACIES AND STRUCTURE SECTIONS FOR THE MAYAGÜEZ GROUP
In the eastern half of the area the mudstone lithology occurs above the Sabana Grande andesite as far south as the Tea syncline. The Brujo limestone is mapped as Parguera limestone.

Yauco mudstone.—Mudstone, minor tuff, and rare conglomerate are herein named the Yauco mudstone. These are the rocks called "strongly bedded shale" and "red shale around Mayagüez" by G. J. Mitchell; he named these the Río Yauco shale (1922, p. 249):

"The Río Yauco shale is characterized by a high content of iron-bearing matter, which on weathering has produced large areas of reddish and yellowish soil, and by its thin-bedded and laminated structure, blocky fracture, light weight, and porous character. . . . The unweathered rock is a black shale."

Hubbard (1923, p. 29) named these rocks the Río Yauco series. "Río" has been dropped to avoid confusion with other Puerto Rican formational names.

The Yauco mudstone occurs in great thickness in the northern part of the area and as thinner lenses or tongues in the south. Fresh exposures are rare in the Las Vegas syncline; a deep road cut on Route 357 northwest of Maricao shows fresh rock, and good outcrops are exposed in the upper reaches of the Río Rosario. Route 120, less than 1 km east of the area, between the Río Blanco contact and the intersection of routes 120 and 106 shows good weathered exposures, as does a dirt road extending north from Route 106, 1.75 km from Mayagüez.

SEDIMENTARY FEATURES: The Yauco mudstone is composed of foraminiferal tuffaceous mudstone (Pl. 4, fig. 1) with minor tuff, wacke, conglomerate, and bedded chert. Most of the beds are 1–15 cm thick, and they average 8–10 cm. More calcareous or tuffaceous layers average 20–80 cm. Fissility is rare; bedding is fairly regular in any single outcrop.

Slump structures and graded bedding are rare, but wisp structures are common. Bedded tuff forms 20 to 60 per cent of the Yauco mudstone; the larger tuff and flow units have been separated as the Maricao basalt.

The mudstone is very deeply weathered in almost every exposure. The only extensive fresh outcrops within the area are in the Tea syncline. Generally speaking, the more fine-grained, thin-bedded rocks weather to red clays, and the slightly coarser, more tuffaceous, thick-bedded rocks weather to yellow clays. The yellowish clays are commonly slightly granular. Clays derived from bedded material commonly retain traces of the bedding. Extreme weathering produces a red clay with white subparallel streaks. These white streaks are quite irregularly bounded, are 1–2 cm wide, and are about 1–2 cm apart. The streaks commonly parallel bedding and seem to mark zones where iron in the red clay has been reduced, perhaps around roots or by organic-rich ground water. The zones are restricted to bedding surfaces and joint cracks, the easiest paths for solutions to follow through the rock.

In the intermediate step between fresh rock and a saprolitic clay, a very porous "rock" is formed (Pl. 3, fig. 1). The cavities are formed by leaching of calcareous material, largely Foraminifera. The remaining matrix is commonly siliceous, and the rock may be mistaken for weathered bedded chert.

Microscopically, the mudstone shows a gray-green or brown to whitish noncalcareous matrix of clay-sized material, with calcareous fragments and angular crystal fragments usually 20–30 per cent of the rock and about 0.05 to 0.1 mm in size. The crystal fragments are broken feldspar and rare

quartz, commonly unaltered but in some cases partially altered to calcite. Pyroxene and hornblende crystals are also rare. Organic fragments are planktonic Foraminifera, Radiolaria, small shell fragments, and rare echinoderm spines. Chloritic material is rare; pyrite-rich mudstones have been found, but their distribution is unknown.

About half of the mudstone has a uniform texture, and half contains light or dark discontinuous streaks or wisps—laminae or patches of a lighter or darker material (cf. Berkey, 1915, p. 21–22). The streaks are 1–3 mm wide and of varying length. Dark laminae seem to be formed by concentrations of carbonaceous or coarse tuffaceous material. Some parallel the bedding, and others are contorted (rolled or truncated by other laminae). They appear to be wisps of slightly different material, brought in by turbidity currents or other current action.

Greatly fractured bedded chert lenses north of Mayagüez at Punta Algorrobo and inland from the Point were discussed by G. J. Mitchell (1922, p. 250) and Hubbard (1923 p. 24, 29). Thin sections show cryptocrystalline silica with circular ghost structures, possibly of Radiolaria. Some rock or mineral fragments and some iron oxide grains are present, the latter forming long thin laminae parallel to the bedding. The cherts are probably formed by local silica enrichment of tuffaceous mudstones due to volcanism.

HORMIGUEROS SYNCLINE: The Yauco mudstone forms narrow belts on the limbs of the Hormigueros syncline. It averages 250 m in the north limb and ranges from 0 to 30 m in the south limb, thinning toward the east in both limbs. The mudstone also occurs in the Guanajibo region in small synclines and synclinal basins on the serpentinite and the Río Loco formation. Here it averages 150 m in thickness. Fresh exposures are visible where Route 361 crosses the outcrop belt 2 km north of San Germán and in a railroad cut on Route 102 at the outskirts of Cabo Rojo.

Medium-grained tuff occurs with the mudstone in the southern limb near the eastern border. This outcrop belt and the exposures near Cabo Rojo commonly weather in blocks of large (1 m) "beds", each containing many laminae. This type of weathering is also found in mudstones north of Sabana Grande (T. R. Slodowski, 1956, unpub. Ph.D. thesis, Princeton Univ., p. 18).

TEA SYNCLINE: In the Tea syncline are two large tongues of the Yauco mudstone, one at the base of the syncline resting upon serpentinite and the other near the center of the north limb.

In most exposures the lower tongue is partially to completely silicified, showing a hard intensely fractured rock with abundant calcite veins, in which attitudes are rare and unreliable. Silicification is also found at the base of the Mayagüez group in the southern structures, especially in the Melones syncline.

The upper tongue forms the crest of the range of hills south and southeast of San Germán. Exposures are on routes 4 and 118 (Pl. 3, fig. 2); the best exposures are on Route 118 but only the lower half of the unit is unaltered. The upper half has been silicified and silicated (*See* Economic Geology). Even the altered part of the section retains a medium- to thick-bedded appearance, the original rocks were probably more calcareous than typical Yauco mudstone. A 20–25-m thickness of 8–25-cm beds of fragmental limestone occurs about 12 m above the base of the upper tongue on Route 118. To the west, however, the tongue is largely mudstone. The graded bedding agrees in general with the regional structure.

Several andesitic flows and diorite porphyry sills are exposed in the sequence on the Tea road (Route 118). At the southern edge of the upper tongue on the Tea road is a conglomerate lens with pebbles of basalt, greenish porphyry, and recrystallized limestone in a pale-violet matrix, probably tuffaceous. The pebbles are rounded to subangular and average 3–5 cm in diameter. The proximity of this lens to a sheared fault zone perhaps accounts for the recrystallization of the limestone pebbles.

PALEONTOLOGY AND AGE: The samples, microfaunas, and ages are listed in Plate 6; sample locations are on Plate 1. Many of the faunas in the Yauco mudstone are more than 90 per cent pelagic, and some samples contain stunted faunas (E. A. Pessagno, Jr., 1955, unpub. manuscript, Princeton Univ.). Samples with significant ages in the Las Vegas syncline are: (1) from the center of the syncline PR2863, Late Cretaceous, probably Campanian; PR2901, Campanian; (2) from the south edge of the syncline PR2764, Turonian to Campanian, possibly Campanian; (3) from north of Mayagüez, near the north edge of the syncline PR2884, Turonian to Campanian. Determinations to the east range from Campanian or possibly Santonian to early Maestrichtian (Paul Bronnimann, personal communication). Thus the age range of the Yauco mudstone (and also the Mayagüez group) in the Las Vegas syncline is Campanian to Maestrichtian, possibly as old as Turonian. This is the same range found elsewhere in southwest Puerto Rico for the entire Mayagüez group. Microfaunal samples from the Yauco mudstone in the Hormigueros and Tea synclines have a Turonian to Campanian range.

CONTACT RELATIONSHIPS: Bedding in the Yauco mudstone generally parallels the contact with the Río Loco lava, but some exposures show bedding truncated at the contact. In the Hormigueros syncline, on the dirt road from Rosario north to Limón, the contact truncates bedding in the Yauco mudstone at an angle of 20°, and near the contact

the mudstone is fissile. This exposure is interpreted as evidence of thrust faulting along the contact, occurring locally in other places between Sabana Grande and Mayagüez.

The lenticular nature of the Maricao basalt within the Yauco mudstone is shown on Plate 1. Relationships of the Río Blanco formation and the Yauco mudstone are not definitely known. The Río Blanco is at least in part ?Campanian to ?Maestrichtian. Field relationships show that the contact between the two formations parallels the strike of both units, and as yet no definite evidence of faulting has been found; however, the contact is considered as a fault of unknown displacement, bringing Río Blanco strata into contact with the Yauco at the northern edge of the Las Vegas syncline.

In the Tea syncline a gradational contact between the Sabana Grande andesite and the Yauco mudstone (upper tongue) is exposed on Route 118. Calcareous massive tuffs and breccias of the andesite grade into medium- or thick-bedded tuff and minor mudstone. The contact is drawn where bedding becomes prominent.

Parguera limestone.—The Parguera limestone is composed of buff to gray medium-bedded calcilutite and medium-bedded to massive fragmental limestone (microcoquina) with less than 15 per cent tuff and a slightly smaller amount of calcarenite. The type area is the range of hills north of the fishing village of La Parguera (Pl. 3, fig. 3). Excellent exposures are in the sea cliffs east of the town. The formation is also exposed as far north as Hormigueros (Pl. 3, fig. 4) and as far east as Guánica. Fragments of the unit occur in younger conglomerates near Cabo Rojo.

Thick-bedded and massive fragmental limestone, commonly with wavy bedding, is found at the base of the unit and in some places also near the top. Reworking of fossil debris is noted near the top of the unit, along with an increase of the clastic component, concentration of glauconite, and a thickening of bedding.

Diagnostic features are the abundance of marly weathering calcilutite, the common presence of glauconite, and the rarity of noncalcareous debris.

The Parguera limestone has been described by T. R. Slodowski (1956, unpub. Ph.D. thesis, Princeton Univ., p. 31–52) as part of the Ensenada formation. G. J. Mitchell (1922, p. 252) described the exposures at Ensenada as the "Ensenada shale", his term for medium-bedded calcareous material. The unit is redefined because the Ensenada formation as defined by Slodowski (p. 31) includes limestones and volcanic rocks that the present author places in the San Germán formation.

SEDIMENTARY FEATURES: Microcoquina (fragmental limestone) and fragmental calcilutite are present in the Parguera limestone. Microcoquina (Pl. 4, fig. 2) occurs in all the limestone units in the Mayagüez area; it is most characteristic of the massive limestones. It forms large blocks of medium-bedded to massive, buff to light-gray rock, in most cases capping hills or forming a karst terrain. The rock contains Foraminifera, Radiolaria, and well-sorted (0.7–1.0 mm) fragments of microfossils, rudists and other mollusks, algae, echinoderms, and sponge spicules. Pellets are found, more commonly in the Brujo and Cotui limestones than in the Parguera. Magnetite grains, porphyry fragments, and some lithic fragments of microcoquina and calcilutite occur. Many of the larger fragments and the interior structure of some Foraminifera have been recrystallized. The matrix, 40–70 per cent of most rock specimens, is white or yellow calcite, commonly also recrystallized. Under high magnification the unaltered matrix is a turbid mass of carbonate and clay minerals, probably of both clastic and biochemical origin (Pettijohn, 1949, p. 305).

Limestone with greater than 70–80 per cent matrix is herein termed fragmental calcilutite. This lithology, generally medium-bedded, contains more Foraminifera than fragments, and many fragments are as small as 0.07 mm.

Tuffaceous material is common in the east part of the area and near the base and top of the Parguera limestone in the Parguera anticline.

Glauconite occurs as pellets, shreds, and flattened worm (?) tubes in relatively coarse-grained microcoquinas. Many of these beds also contain worn Foraminifera, evidence of reworking. Most glauconite concentrations are found in the younger (northernmost) rocks in the Parguera anticline.

Conglomerate lenses are rare in the Parguera limestone. They are exposed in the northern quarry north of Hormigueros, the sea cliffs east of Parguera, and in the Vertero hills. Some are intraformational, containing sparse pebbles distinguishable from the matrix only by color or degree of compaction. Other conglomerates occur at or near the base of the formation and are described in the section on contact relationships.

Patchy but widespread silicified zones up to 600 m in horizontal extent occur near the base of the Parguera limestone and in some places also following faults. Silicification primarily affects the matrices of the fragmental rocks. One sample from the Sierra Melones contained 0.01—0.02-mm dolomite rhombs scattered through the finely recrystallized matrix. These silicification zones are similar to zones in the

Yauco mudstone along the serpentinite south of San Germán. Here also silicification is common, and dolomite rhombs are present in one sample, but the host rocks are foraminiferal mudstones. The silica in both cases is probably introduced along the lower contact (with serpentinite) or along faults.

HORMIGUEROS SYNCLINE: The uppermost unit in the Hormigueros syncline is the Parguera limestone, composed of calcilutite and microcoquina, with some shale near the center of the syncline, east of the volcanic lens. The more limy rocks have thin shale or mudstone partings along bedding surfaces. Calcarenite and thick-bedded or massive microcoquina are found near the base of the unit, especially on the north side; on the south side limestone interfingers with amygdular volcanic rock, probably lava and tuff. Good exposures are seen in the quarries on Route 344 north of Hormigueros (Pl. 3, fig. 4) and on Route 346. Symmetrical ripple marks near the end of Route 344 confirm the overturning shown in the regional structure. Within the limestone unit are lava and breccia very similar to the Sabana Grande andesite occurring beneath the unit. The breccia contains fragments of the Parguera limestone.

PALEONTOLOGY AND AGE: Plate 6 lists the microfauna from the Parguera facies and the age determinations.

Age determinations from microfaunas in the Parguera anticline, Vertero syncline, and Melones syncline range from Turonian to Santonian, to early Maestrichtian.

G. J. Mitchell (1922, p. 286–287) found specimens of the echinoid *Hemiaster berkeyi* near Ensenada in rocks which in the Parguera area are correlated with the Parguera limestone. Specimens of the rudist *Barrettia* found in the Parguera limestone are described in Regional Geology.

In the Hormigueros syncline, the highest beds in the Parguera limestone are probably early Maestrichtian and the lowest Turonian to Campanian.

CONTACT RELATIONSHIPS: In the southern structures the Parguera limestone lies probably conformably on the Río Loco formation or, where that is absent, unconformably upon the Bermeja complex. Where its top is exposed the Parguera formation is covered probably disconformably by the Melones limestone.

At the west end of the Vertero hills limestone rests on the serpentinite. There, where a dirt road crosses the hills, a small outcrop

PLATE 2.—PHOTOMICROGRAPHS OF IGNEOUS ROCKS

FIGURE 1.—PR27, serpentinite microbreccia from the Bermeja complex west of Sabana Grande (Route 365) in the Yauco area. Angular serpentinite fragments in a fine-grained isotropic matrix. White veinlets and ovoid grains are calcite; some serpentinite veinlets also occur. (Plain light)

FIGURE 2.—PR2766, analyzed specimen of bronzite andesite porphyry, Río Loco formation east of Mayagüez. Clustered aggregates of twinned plagioclase. Isolated laths of serpentinized bronzite in upper half of photograph, also fresh augite crystals. Serpentine vein in lower right. Matrix is opaque. (Crossed nicols)

FIGURE 3.—PR2866, basalt porphyry, Maricao basalt northeast of Mayagüez. Large crushed and broken augite crystal and smaller completely altered feldspar crystals in an isotropic matrix. Black spots are opaque minerals. The rock is probably a tuff. (Plain light)

FIGURE 4.—PR29, analyzed specimen of quartz diorite porphyry from Route 118. Rounded euhedral plagioclase with altered rims; rounded (partially resorbed?) quartz grains showing different extinctions, perhaps indicating differential movement. Small amphibole crystals, now altered. (Crossed nicols)

PLATE 3.—OUTCROPS

FIGURE 1.—Weathered Yauco mudstone exposed in the southern outskirts of Mayagüez. The rock has been leached of its calcareous content, principally Foraminifera, and is now a porous siliceous material.

FIGURE 2.—An exposure of a calcareous facies of the Yauco mudstone, looking west near the crest of Route 118, showing a small thrust fault of less than 1 m displacement. The beds are dark limestone with some mudstone interbeds. The hat above the fault shows the scale.

FIGURE 3.—Parguera limestone along the coast east of Parguera. The fold cannot be traced far and was probably formed by penecontemporaneous slump. The photograph has about a 4-foot view.

FIGURE 4.—Parguera limestone in the southern quarry on Route 344 north of Hormigueros. Medium-bedded calcilutite with some mudstone; two conglomerate beds seen in the upper half of the rear wall of the quarry.

PHOTOMICROGRAPHS OF IGNEOUS ROCKS

FIGURE 1

FIGURE 2

FIGURE 3

FIGURE 4

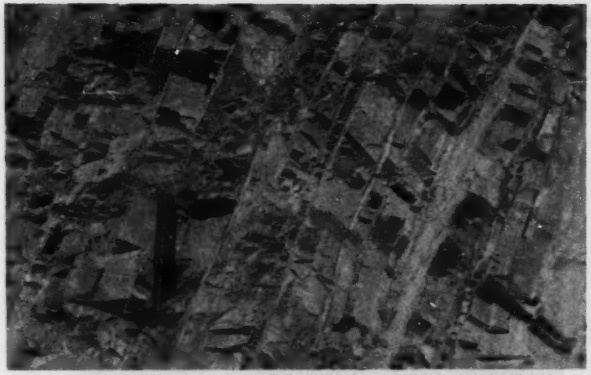

FIGURE 1

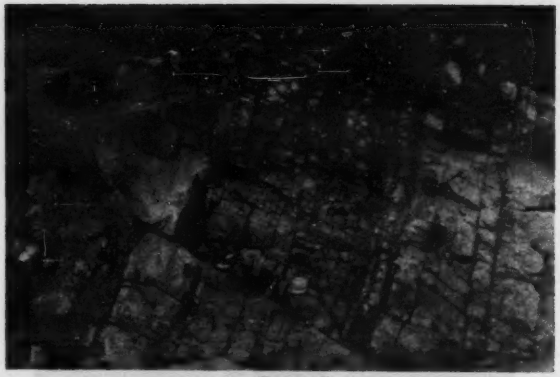

FIGURE 2

FIGURE 3

FIGURE 4

OUTCROPS

FIGURE 3

FIGURE 4

OUTCROPS

FIGURE 1

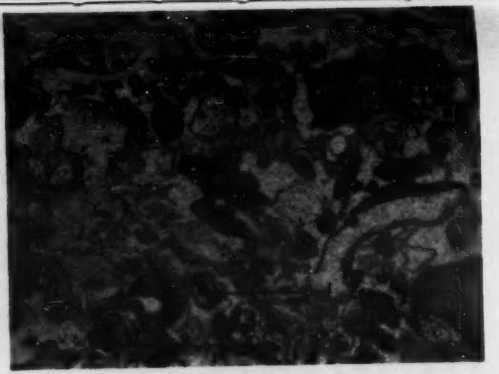

FIGURE 2

FIGURE 3

FIGURE 4

PHOTOMICROGRAPHS OF SEDIMENTARY ROCKS

FIGURE 1

FIGURE 2

COTUI LIMESTONE OUTCROPS

exposes conglomerate containing chert pebbles and chromite grains probably from the Bermeja complex, Parguera limestone pebbles, and some shattered shale.

The Parguera limestone and the serpentinite are in contact on the coast at the Sierra Melones. Here the following sequence occurs:

(4) Paraguera limestone

(3) A 2–3-m zone of conglomerate or breccia containing angular, microcrystalline chert fragments and chromite grains in a yellowish siliceous matrix

(2) Zone of siliceous serpentinite breccia

(1) Serpentinite with amphibolite inclusions (poorly exposed)

Zones (2) and (3) are interpreted as a pre-Parguera lithified zone of weathering on the serpentinite. The chert and chromite are apparently derived from the Bermeja complex; no serpentinite pebbles were found in the upper zone, probably because serpentinite decomposes quickly. These outcrops indicate that the Parguera limestone is deposited unconformably upon the serpentinite.

Elsewhere in the area the lower parts of the Mayagüez group contain pebbles of amphibolite. Amphibolite has been found in place elsewhere in the Mayagüez area only as inclusions and possibly as lenses in the serpentinite. Bedding in the Mayagüez group is everywhere conformable with the contact.

The contact of the Parguera and Río Loco formations is not exposed, but the units are considered conformable because of their parallel outcrop patterns and strikes.

The top of the Parguera limestone is exposed only in the Sierra Melones. Here in the center of the Melones syncline is an oval exposure of Melones limestone. The borders of this area parallel attitudes in both formations; there is no basal conglomerate. Reworking in the uppermost Parguera beds here, however, suggests a disconformable relationship.

Melones limestone.—The dark argillaceous lenticular limestone with banded tuff or volcanic wacke and mudstone exposed in the center of the Sierra Melones is herein called the Melones limestone. The lowest part of the unit is a massive or thick-bedded dark argillaceous limestone or, where this is absent, a thin fossiliferous medium-bedded mudstone. This grades upward into medium-bedded fossiliferous calcareous mudstone. Above are banded volcanic wacke, conglomeratic tuff or wacke, fragmental calcilutite, and more argillaceous limestone. The top of the formation is not exposed in the area; an approximate minimum thickness is 175 m. The formation is also present in the Tea syncline, where it occurs as lenses in the El Rayo volcanic rocks.

SEDIMENTARY FEATURES: This fragmental argillaceous limestone (Pl. 4, fig. 3) contains 20–80 per

FIGURE 2 COTUI LIMESTONE OUTCROPS

PLATE 4.—PHOTOMICROGRAPHS OF SEDIMENTARY ROCKS

FIGURE 1.—PR2826, foraminiferal mudstone from the Yauco mudstone east of Mayagüez. Shell fragments and Foraminifera in a turbid brown matrix. *Guembelina* sp., *Globigerina* spp., *Globotruncana* sp. (upper right). (Plain light)

FIGURE 2.—PR2732, fragmental limestone from the San Germán formation near Rosario. Mollusk fragments, miliolids, large Foraminifera in a crystalline calcite matrix. (Plain light)

FIGURE 3.—PR369, Melones limestone, showing dark matrix and fragments of gastropods, large Foraminifera (fan-shaped forms are *Kathina*), miliolids (bottom left and upper left), and other mollusk fragments. (Plain light)

FIGURE 4.—PR2053, pellet limestone, Brujo limestone northwest of Lajas. Pellets are indistinctly shown in lower half of the photograph. Some form cores for oölites, showing radial and concentric structure near center of the photograph. Spotted fragments in left half are algae; matrix is largely recrystallized. (Plain light)

PLATE 5.—COTUI LIMESTONE OUTCROPS

FIGURE 1.—View from near Llanos Tunas on Route 312, south of Cabo Rojo, looking northeast at the Cotui limestone member of the San Germán formation, showing its gentle northward dip.

FIGURE 2.—View looking south at the south edge of the Valle de Guanajibo, showing the Cotui limestone dipping gently southward, resting on sugar-cane-covered volcanic slopes. These cliffs are G. J. Mitchell's (1922) type locality for the "San Germán limestone".

cent fragments of shells such as mollusks, large Foraminifera, rudists, and echinoid spines, algal fragments, and coral fragments in a yellow-brown to light-brown matrix of 0.01- to 0.03-mm calcite grains, commonly with argillaceous or carbonaceous borders. Most fragments are 0.25 to 0.5 mm, subangular to rounded, poorly sorted, and recrystallized.

A fetid odor (H_2S) is common when a specimen is chipped, probably coming from black (carbonaceous?) calcite which fills cavities and replaces shell fragments. Up to 15 per cent tuffaceous material is present in some specimens, and *Kathina jamaicensis* is a common fossil.

Bedding, where present, is commonly wavy. The limestone forms low ridges or elongate hills; lens thicknesses range up to 100 m, but most are 15–30 m thick. The most continuous lens in the Tea region is almost 3 km long. In the Sierra Melones region the massive or wavy bedded limestone grades along strike into medium- or thin-bedded calcareous friable mudstone, containing abundant gastropods and pelecypods, and some coral. This unit marks the base of the formation in the western Sierra Melones.

Wacke, common in the Melones formation, is composed of fragments of porphyries, green tuff, chert, pyroxenes, and feldspars. Authigenic quartz is present on some chert grains. The matrix is in part calcareous, in part argillaceous.

A distinctive feature of the tuff and wacke is the presence of thin (0.5–1.0-cm) laminae composed of magnetite grains and brownish volcanic fragments. The laminated tuff interfingers with medium-bedded calcilutite. Conglomeratic tuff or tuffaceous conglomerate, present along the north side of the Sierra Melones, contains fragments and pebbles of the massive underlying limestone.

TEA SYNCLINE: Lenses of the Melones limestone occur at different stratigraphic levels within the upper part of the El Rayo volcanic formation in the Tea syncline. Medium-bedded calcilutite, calcareous wacke, and laminated tuffaceous wacke are seen near the edge of the Valle de Lajas, in stratigraphically high parts of the El Rayo.

PALEONTOLOGY AND AGE: The microfauna (Pl. 6) indicates a Campanian to Maestrichtian or possibly Maestrichtian age for the Melones limestone. Macrofossils identified from the friable mudstone facies of the Melones limestone by Norman F. Sohl of the U. S. Geological Survey include:

PR341: *Turritela trilira* Conrad (late Campanian-Maestrichtian of Gulf Coast), *Trochacteon* cf. *T. variabilis* Böse (Maestrichtian of Mexico), *Biradiolites*? sp., and *Cuneolus*? sp.;

PR2149: *Pseudocucullea* sp. Solger (Campanian-Maestrichtian of Africa and northern South America, similar to *P. gregoryi* Olsson of the Maestrichtian of Peru);

PR2294, 2411, 2412: Astartid-like pelecypod, venericardidlike pelecypod, abundant tubes of wood-boring worm;

PR386: *Trochacteon* sp. (late Late Cretaceous?);

PR365: *Spondylus* sp., *Venericardia*? sp., micrabacid coral, and oyster fragments encrusted with bryozoans;

PR464: *Ostrea* (*Lopha*) sp.

These specimens indicate a possible Campanian-Maestrichtian age.

Three rudists belonging to the *Titanosarcolites* fauna of L. J. Chubb (1955, unpub. paper presented at 1st Caribbean Geological Conference, Antigua, B. W. I., December, 1955) have been identified from the formation:

PR388: *Titanosarcolites*, near *T. giganteus*

PR390: probably *Praebarrettia*, near *P. sparcilirata*

PR2907: probably *Orbignya guitarti* Palmer

The identifications are by Chubb (Personal communication). The three species are found in Cuba; *P. sparcilirata* and *T. giganteus* are also found in Jamaica and St. Croix. *T. giganteus* has also been reported from the state of Chiapas, Mexico (F. K. G. Mullerried, *in* Chubb, 1955b, p. 182). Chubb (1955b, p. 183–185) has discussed this group of rudists and concludes that they are Maestrichtian.

The uppermost portion of the Parguera limestone in the Sierra Melones, immediately below the Melones limestone, is dated as Turonian to Maestrichtian, possibly middle Campanian, on the basis of microfossils.

The San Germán formation unconformably overlies the Mayagüez group. The San Germán is dated as Upper Cretaceous, probably Maestrichtian.

In Jamaica the limestone bed containing the *Titanosarcolites* fauna is 61 m thick in places and occurs about 30 m below a 12- to 15-m limestone unit dated as late Maestrichtian (Chubb, 1955b, p. 183). This implies that the limestone is pre-latest Maestrichtian.

In summary: the San Germán formation is post-Melones, probably Maestrichtian; the Parguera limestone is pre-Melones (Turonian to Maestrichtian); the Melones limestone foraminiferal fauna is Campanian to Maestrichtian, possibly Maestrichtian; the Melones limestone macrofossils other than rudists are Campanian to Maestrichtian; Melones limestone rudists belong to the *Titanosarcolites* fauna, dated by Chubb as Maestrichtian; the *Titanosarcolites* fauna in Jamaica is pre-latest Maestrichtian. These

various lines of evidence indicate the age of the Melones limestone in the area studied is Maestrichtian.

CONTACT RELATIONSHIPS: The Melones limestone in the Tea syncline occurs as lenses in the El Rayo volcanic rocks, and in the Melones syncline it overlies the Parguera limestone. All contacts seen were sharp and parallel to bedding.

Brujo limestone.—The Brujo limestone is the massive limestone equivalent of the Parguera limestone. It contains massive or thick-bedded microcoquina, pellet limestone, some calcilutite, and minor wacke and mudstone. Lithologically the Brujo limestone is identical to the Cotui limestone of the San Germán formation; the two are differentiated only by structural or age relationships. The Brujo limestone is considered Turonian to Campanian and is commonly strongly folded, and limestone of the San Germán formation is probably Maestrichtian and is commonly gently folded. Possibly some exposures labeled Cotui limestone might, with further study, be correlated with the Brujo limestone, or *vice versa*.

Microcoquina predominates within the unit, and pellet limestone is also common. The limestone is massive to thick-bedded with undulating bedding planes, containing fragments of mollusks including gastropods and rudists and some fragments and tests of larger Foraminifera.

Brujo limestone occurs in three areas:

(1) Near El Brujo a massive gray fragmental limestone (microcoquina) forms a ridge trending northeastward. This is the type section for the Brujo limestone; the limestone probably dips northwest beneath a series containing conglomerate, breccia, limestone, and volcanic rock, part of the San Germán formation. A pebble from the conglomerate (PR2005) is dated as Turonian to Campanian. Southeast of the El Brujo ridge the El Brujo fault separates the limestone from another area of San Germán formation to the south.

There are three age determinations from the El Brujo ridge. A marly limestone outcrop (PR433) contains abundant gastropods, identified by N. F. Sohl (Personal communication) as *Nerinea* (*Plesiotygmatis*) *cf. N.* (*P.*) *burckhardti* Böse. In Mexico this species occurs in the Cárdenas formation of supposed Maestrichtian age.

Rudists of the genus *Barrettia* were seen in the massive limestone near where the dirt road crosses the ridge north of El Brujo. *Barrettia* has been dated as Campanian on the basis of Foraminifera in the Parguera limestone and is considered late Turonian to Coniacian elsewhere (L. J. Chubb, 1955, unpub. paper presented at 1st Caribbean Geological Conference, Antigua, B.W.I., December, 1955). Inasmuch as rudists are found in the San Germán formation as components of conglomerates, the age determination has little value.

Foraminifera from two samples (PR435; PR2185) collected from thin-bedded glauconitic mudstones immediately above the massive limestone at El Brujo were dated by E. A. Pessagno, Jr., as middle Campanian. This places the mudstones within or below the middle Campanian; mudstones may, however, be gravity-slide material similar to that found at the base of the San Germán formation elsewhere.

Structural evidence indicates the limestone is pre-San Germán. The paleontological evidence listed does not contradict this, and therefore the limestone is considered Turonian to Campanian.

(2) Northwest of Lajas the Yauco mudstones pass to the west abruptly into massive limestones. These limestones, although lithologically similar to San Germán limestones less than half a kilometer to the west, are correlated with the Brujo limestone because of the structural similarity. The limestones are thick-bedded and massive microcoquinas and fragmental pellet limestones. No age determinations were made; only Radiolitidae were found. The Yauco mudstone along strike of these limestones is possibly Campanian. Small limestone outcrops occur along the northern border of the unit as far east as Route 4.

(3) Southwest of Cabo Rojo near Punta Guaniquilla is a blue-gray massive limestone, dipping about 40° N. and striking west-northwest. It is perhaps 20 m thick, with sparse bedding planes. It contains the same faunas (PR2217, PR2218, Pl. 6) and is correlated with the Brujo limestone because of their age of Turonian to Campanian, possibly Campanian.

Maricao basalt.—Lava and flow breccia with minor breccia and tuff occur above and as lenses in the Yauco mudstone in the Las Vegas syncline and to a lesser extent in the Hormigueros syncline. The unit, because of its good exposure on the Río Maricao north of Maricao, is named the Maricao basalt. According to an analysis (PR7, Table 1) and the mineralogical composition, the rock is trachybasalt in the sense of Williams, Turner, and Gilbert (1954, p. 57–58) and Washington (as the trachydolerite series, 1897, p. 366), an intermediate between trachyte and basalt. The analysis falls between analyses of absarokite and shoshonite made by Iddings (1895, p. 938, 944, 952) and is similar to an analysis that Iddings states is transitional.

PETROGRAPHY: The lenses are as large as 6–8 km long and 1–2 km wide. Basalt porphyry, the most common rock type, occurs as flows, as fragments in breccia, and perhaps also as small intrusions. The proportion of lava to tuff increases from west to east both within lenses and between lenses. Breccia

is less abundant than in the volcanic rock to the south.

Fragmental rocks are present, although not as common as in the Sabana Grande andesite to the south. Most fragments are varieties of the basalt, and the matrix of the fragmental rocks is similar to the basalt. These appear for the most part fragment-rich flows rather than fragmental tuffs.

Spheroidal weathering is characteristic of the basalt. Outcrops show large exfoliating spherical boulders in a red or orange-yellow soil, more granular than soils on the Yauco mudstone. Route 348 from Mayagüez through Rosario to Route 119 crosses many gullies filled with boulders from exposures of the basalt. Fresh exposures show a hard dark porphyry with prominent amygdules and pyroxene crystals.

BASALT PORPHYRY (PL. 2, FIG. 3): The dark-gray-green groundmass contains ?glass and magnetite, pyroxene, and feldspar grains; the grains are 0.1–0.2 mm. Amygdules (2 per cent) have been identified as chlorite, calcite, quartz, ?prehnite, and pumpellyite (C. A. Kaye, personal communication). Phenocrysts of approximately equal amounts of green augite and plagioclase make up 35 to 40 per cent of the specimens examined. Magnetite and serpentinite pseudomorphs after ?olivine make up less than 4 per cent. Augite phenocrysts are green, fresh crystals and crystal fragments averaging 3–4 mm, although 7–10 mm crystals are not rare. There are poikilitic enclosures of chlorite (altered ?glass), serpentine (altered ?olivine), and plagioclase. Plagioclase phenocrysts, averaging 0.5–1.0 mm, are generally sericitized, but some fresh laths do occur. Serpentine pseudomorphs after ?olivine are present both as phenocrysts and included in crystals of augite.

HORMIGUEROS SYNCLINE: In the Hormigueros syncline the Maricao basalt is found in a poorly defined belt trending east-southeast from Mayagüez in the north limb of the syncline resting upon the Yauco mudstone and in sparse outcrops on the south limb.

AGE AND CONTACT RELATIONSHIPS: The Maricao basalt, lenticular within the Yauco mudstone, is thus necessarily of the same age (Turonian to Maestrichtian). No fossils have been found.

Sabana Grande andesite.—The Sabana Grande andesite was defined by T. R. Slodowski (1956, unpub. Ph.D. thesis, Princeton Univ., p. 16) as the Sabana Grande formation. He noted:

"A heterogeneous assemblage of andesitic lava flows with subordinate dark, calcareous mudstone comprises the Sabana Grande formation. Bedded and graded very fine to coarse tuffs are rare in the formation. Relatively fresh, resistant, angular inclusions of andesite porphyry in the lava flows are common; in some outcrops they appear to be similar to the matrix, while in others they are apparently foreign."

The mudstone in the Sabana Grande formation of Slodowski is correlated with the Yauco mudstone in the Mayagüez area.

The largest known exposure area of the Sabana Grande andesite is the Hormigueros syncline. Other exposures form small synclines in the Guanajibo region, a tongue in the Tea syncline, and outcrops in the Yauco area. The best exposures are on routes 348 and 119 connecting Mayagüez, Rosario, and San Germán.

PETROGRAPHY: The unit is composed of andesite breccia, flow breccia, and tuff, with minor basalt lava; lateral changes of texture and lithology are common. Most rock specimens contain some fragments, and many are breccias. Lava and tuff are most common at the top of the unit, with breccia below. At the top of the unit there is a breccia containing mainly green, red, and brown aphanitic volcanic fragments. The matrix is calcareous, the fragments andesite porphyry and tuff. This breccia grades into conglomerate and volcanic sandstone, also calcareous.

At the base of the andesite in the Tea syncline and the Guanajibo anticline are lenses of poorly sorted conglomerate that contain rounded to subangular (1–10-cm) pebbles and granules of porphyries, radiolarian chert, and amphibolite or partially amphibolitized diabase. The chert and metamorphic pebbles are from the serpentinite complex below; the porphyries are probably derived from contemporary vulcanism. The matrix of the conglomerate is noncalcarceous tuffaceous mudstone containing some quartz and feldspar fragments.

Tuff and andesite porphyry in this unit are similar to rocks in the San Germán formation but have less abundant and less altered hornblende phenocrysts. Plagioclase also forms phenocrysts. The matrix contains feldspar microlites and pyroxenes and is in many cases altered, probably silicified.

Breccias are composed of porphyritic andesite or basalt fragments in an andesitic (?) matrix. The matrix weathers readily, but in some cases tuffaceous material is distinguishable. The matrix is purple, grading into gray or red. Quartz-epidote veins are common. Fragments range from 1 cm to 6 m, averaging 9 to 30 cm; three varieties make up 80–90 per cent of the total. These are: (1) pyroxene basalt porphyry, similar to specimens described in the Maricao basalt; (2) hornblende andesite porphyry, similar to lava and tuff found with the breccia, in many places silicified; (3) greatly weathered feldspathic pyroxene porphyry with a light-colored matrix. The fragments are commonly angular; some are subangular to subrounded. In typical outcrops the silicified andesites weather out from the surface.

TEA SYNCLINE: The Sabana Grande andesite in

the Tea syncline contains andesite lava, tuff, breccia, and a basal member of siltstone and conglomerate. The percentage of breccia and tuff increases upward, and the rocks grade into the Yauco formation. Graded bedding occurs in the basal conglomerate, in general oriented in agreement with the regional interpretation.

PYROXENE ANDESITE PORPHYRY (ANALYZED SPECIMEN PR66, TABLE 1): The groundmass contains small opaque grains (7 per cent), feldspar grains, and altered ?glass. Phenocrysts make up 50 per cent of the analyzed specimen, consisting of plagioclase (calcic andesine: 35 per cent), pseudomorphs after ?pyroxene (12 per cent), and opaque minerals (3 per cent). Plagioclase occurs as twinned and zoned laths averaging 0.1–1.0 mm long, commonly altered to sericite or calcite. Euhedral pseudomorphs after ?pyroxene, formed of calcite and chlorite, average 1–3 mm. Opaque minerals occur with sphene; few are larger than 0.1 mm.

The texture is pilotaxitic. The chemical composition (Table 1) shows a great deal of secondary calcite. If the 7.5 per cent normative calcite is removed from the analysis and the analysis is recalculated to 100 per cent, the result is: SiO_2, 58 per cent; Al_2O_3, 19 per cent; CaO, 5 per cent. The other oxides are not changed significantly. The recalculated analysis corresponds to a feldspathic andesite with high alumina and low K_2O, and the original analysis is similar to that of a basaltic andesite with low magnesia.

AGE AND CONTACT RELATIONSHIPS: Volcanic rocks of the Sabana Grande andesite are in depositional contact with other units, paralleling bedding in detail in many cases. Within the volcanic unit there is a rough lithologic sequence. Minor conglomerate at the top and bottom show that erosion has occurred at both levels, but the extensive interfingering at the upper contact in the Hormigueros syncline (Pl. 1) and the parallelism of bedding at the lower contact demonstrate the lack of widespread structural breaks.

No fossils have been identified from this unit, but, from its position between the Parguera and Yauco formations, the Sabana Grande andesite can be dated in the area studied as Turonian to Campanian.

El Rayo volcanic rocks.—The El Rayo volcanic rocks were defined by T. R. Slodowski (1956, unpub. Ph.D. thesis, Princeton Univ., p. 24) as the El Rayo formation, composed of "Feldspathic olivine basalt porphyry (90 per cent) with interbedded lenses (about 10 per cent) of volcanic conglomerate and dark massive limestone. . . ." In the Mayagüez area the dark massive limestone has been named the Melones limestone, and the El Rayo volcanic rocks are considered within the Mayagüez group. The El Rayo volcanic rocks include approximately 1000 m of basalt lava, andesite breccia and lava, and minor conglomerate and wacke. The unit is exposed in the Tea syncline and eastward.

PETROGRAPHY: The El Rayo volcanic rocks contain a large amount of andesitic breccia and innumerable smaller bodies of andesite porphyry, probably lava, tuffs, and minor intrusions. All exposures are very badly weathered; fresh rocks are rare, even in the most recent excavations. Alteration is to chlorite, calcite, and other minerals. Amphiboles are commonly replaced by magnetite which later altered to hematite.

The breccia is generally purple or reddish. The matrix seems similar to the fragments but weathers much more rapidly. It contains crystals of plagioclase and amphibole, with occasional pyroxene, and has a tuffaceous appearance. It is commonly partially altered to hematite, as are the fragments. Average size of fragments is 1–10 cm, and the largest seen were 1–2 m in diameter. Fragments of hornblende andesite porphyry predominate, but pyroxene andesite porphyry and basalt porphyry fragments are not rare. The fragments are subrounded to subangular. Amygdules in the flows are in most cases calcite, chlorite, or epidote.

Basalt porphyry lava and some tuff form approximately half of the formation in the Mayagüez area and probably a greater percentage to the east. The rock contains pyroxene phenocrysts up to 1 cm in diameter in a reddish or purple groundmass. Plagioclase phenocrysts are not commonly visible, and olivine, commonly serpentinized, is visible only under the microscope. Chlorite and calcite amygdules are common.

Fine-grained volcanic conglomerate and calcareous tuffaceous wacke occur in small lenses west of Route 118 near the base of the formation, grading into mudstone and bedded tuff on Route 118.

AGE AND CONTACT RELATIONSHIPS: Structural evidence is inobtainable from the massive breccia and lava that make up the greater part of the formation. Trends of the lenses of Melones limestone in the southern part of the unit, as well as attitudes of mudstone, conglomerate, and wacke along the northern border of the unit, indicate that the El Rayo volcanic rocks are conformable with the Yauco mudstone to the north. The Yauco mudstone has been shown to be facing southward and hence stratigraphically below the El Rayo volcanic rocks; age determinations support this interpretation. Thus the El Rayo volcanic rocks are considered part of the north limb of the Tea syncline, Campanian to Maestrichtian in age.

Within the outcrop area of the El Rayo

volcanic rocks and bordering it on the west are volcanic rock and limestone of the San Germán formation. They are thought to overlie the El Rayo formation unconformably. Exposures are poor east of Lajas; there the contact is approximate. East of the contact in the El Rayo outcrop area isolated bodies of limestone and conglomerate of the San Germán formation unconformably overlie El Rayo volcanic rocks.

San Germán Formation

General statement.—The San Germán formation is a thick sequence of andesitic volcanic rock with interbedded conglomerate and lenses of massive limestone. One flow or sill near the base is differentiated as the Cabo Rojo agglomerate; the massive Cotui limestone member occurs commonly near the top of the volcanic sequence (Pl. 5).

The formation is exposed from Punta Guanaquilla eastward to near Susúa, west of Yauco. It has a maximum thickness of 600 m; the Cotui member is at maximum 75 m and the Cabo Rojo agglomerate is at maximum 30 m.

The Cotui limestone is the highest unit in the formation except southeast of Cabo Rojo, where about 150 m of andesitic volcanic rock, shale and conglomerate overlies it. The formation is thickest and developed in greatest variety south and southeast of Cabo Rojo and in the Susúa basin southeast of Sabana Grande. Between these two areas only isolated patches of limestone and minor conglomerate and andesite occur.

The best exposures of the volcanic rocks are on Route 312 south of Cabo Rojo, of the Cotui limestone in quarries along the south edge of the Guanajibo Valley, and of the Cabo Rojo agglomerate on routes 4 and 314.

G. J. Mitchell (1922, p. 253–254) first used the term San Germán to describe the massive limestone herein called the Cotui limestone. T. R. Slodowski (1956, unpub. Ph.D. thesis, Princeton Univ., p. 84) used the name to refer to massive limestone and associated volcanic rocks and conglomerates. This report slightly expands the latter usage. Large gravity-slide blocks derived from older formations occur near the base of and within the San Germán formation, and a block of the San Germán formation itself is exposed near Rosario. These are discussed in the section on Structural Geology.

Cabo Rojo agglomerate member.—Meyerhoff (1933, p. 29) mentions

"... a conglomerate, or agglomerate, conformably associated with a fossiliferous limestone of late Mesozoic age. The boulders in the agglomerate are of two contrasted types: either they are volcanic fragments, or they are worn and altered granitic fragments."

This agglomerate is exposed in a steep-walled, narrow roadcut at km 10.1 on Route 4, 3.5 km south of Cabo Rojo. It is the type locality for the member and is in the middle of a line of outcrops that trends northeast paralleling the base of the Cotui limestone member and is about 130 m stratigraphically below it. Good exposures also occur on Route 314, where the agglomerate is about 80 m below the Cotui limestone member. The agglomerate member is about 50 m thick. R. C. Mitchell (1954, p. 37, 83) and Schuchert (1935, p. 473) also mention the outcrop on Route 4.

The Cabo Rojo agglomerate contains two types of fragments in an andesitic matrix. The matrix and one type of fragment are hornblende andesite porphyries similar to the andesitic flows of the rest of the San Germán formation and are described under that heading. Altered glassy material in the matrix indicates that the rock is an extrusive or a shallow intrusive rock. The other type of fragment is a whitish or pinkish rock that is somewhat weathered in all exposures. It is hornblende andesite or dacite prophyry.

Fragments range from 1 cm up to 1–2 m and are rounded to subangular. Orientation of cobbles and boulders approximating bedding was observed in two exposures on Route 314. This layering is approximately conformable with the nearby limestones, dipping gently to the north. The borders of the agglomerate member were not observed. Borders of some fragments are indistinct, as if some reaction had occurred between fragments and matrix, suggesting that the unit is either an intrusion or a lava flow.

The whitish fragments appear granitic in hand specimens and are no doubt the fragments described by Meyerhoff (1933) and called rhyolite, granodiorite, granite, granulite, and charnockite by R. C. Mitchell (1954, p. 37, 83). The present author saw none of these rock types in any of the exposures shown on Plate 1. The whitish fragments and the andesites of the San Germán formation both have euhedral green hornblende, euhedral plagioclase, and corroded biotite phenocrysts in a fine-grained matrix and thus could have a common origin. The matrix probably owes its light color to alteration.

The author treats the Cabo Rojo member as an agglomeratic lava flow or sill because

has a fairly constant stratigraphic position beneath the Cotui limestone member and because fragments in the agglomerate seem to have reacted with the matrix of the rock. The glassy character of part of the agglomerate matrix and the resemblance of the matrix to andesite flows of the San Germán formation also imply an extrusive or shallow intrusive origin.

Meyerhoff's (1933) and Schuchert's (1935) use of the "granitic" pebbles as evidence for a pre-Mesozoic orogeny in Puerto Rico is not valid if the pebbles are merely andesites. R. C. Mitchell (1954) tentatively considers the member Upper Jurassic(?) because of an erroneous correlation of two different outcrops of the Cotui limestone member with the entire Cretaceous of Puerto Rico. The Cotui limestone is a member of the San Germán formation and is dated as Maestrichtian by two determinations. It is stratigraphically above the Cabo Rojo member. As the San Germán formation is unconformable upon the Mayagüez group, the Cabo Rojo agglomerate member is probably also Maestrichtian. Meyerhoff and Schuchert also date the member as Late Cretaceous.

Cotui limestone member.—Massive, rarely thick-bedded limestone forms a thick unit near the top of the San Germán formation (Pl. 5). Limestone lenses are also found within the andesitic volcanic rock, often associated with andesitic conglomerate. The limestone is defined as the Cotui limestone member; the San Germán limestone of G. J. Mitchell (1922, p. 253–255) includes this and all the other older-sequence massive limestones in this part of the island.

The Cotui limestone includes microcoquina and pellet limestone with uncommon argillaceous limestone. Lenses of dark argillaceous limestone are seen northeast of the main body of limestone southwest of Cabo Rojo. Near Punta Guanaquilla the limestone is thick-bedded; elsewhere it is massive. It usually caps steep-sided hills and in some cases forms karst topography, particularly southwest of Cabo Rojo, and supports a thick vegetation. Rudist fragments are commonly seen as shreds, fine mesh structures, and oval outlines in the light-gray rock. Larger Foraminifera are present, and pelagic Foraminifera are very rare. Chloritized porphyry fragments and angular quartz grains partially altered to calcite form less than 10 per cent of most specimens.

Near the end of Route 314 the lower contact of the limestone is exposed. A red andesite porphyry breccia, in part conglomeratic, with lenses of reddish oölitic pellet limestone similar to the Cotui limestone except in color, is overlain by about 3 to 4 m of the same red massive limestone, which is in turn covered by gray Cotui limestone. The contact of the red and gray limestones is slightly undulatory but is subparallel to the limestone lenses in the volcanic rock below. The red color is caused by partial alteration of volcanic fragments and magnetite grains to hematite. Elsewhere in the Mayagüez area the base of the limestone is gray; in the Yauco area, however, reddish tints are common at the base of both the San Germán and Jicara limestones.

Microcoquina (fragmental limestone), described in the Parguera limestone, also occurs in the Cotui limestone. Microcoquina grades into pellet limestone, whose main component is small pelletlike forms sometimes called pseudo-oölites. About 20 to 30 per cent of the Cotui limestone contains pellets. The pellets are commonly 0.2 to 0.5 mm and are spheroidal or ellipsoidal. The interior of the bodies is generally recrystallized calcite; the exterior is microcrystalline calcite, commonly dark to almost opaque. Pellets occur, as do oölites and shell fragments, in limestone with a large clastic component.

True oölites are found in several pellet-rich specimens (Pl. 4, fig. 4). These have the typical concentric and radial structure and commonly contain nuclei of shell fragments and possibly of pellets. The nuclei fragments are more angular than the uncoated fragments in any given sample. Where oölites and pellets are found together, the oölites can commonly be distinguished by a yellowish tinge; the pellets are gray to white.

Shell fragments (rudists, algae, corals, echinoderms, gastropods) are common. Fragments and tests of large benthonic Foraminifera are common although not abundant. Volcanic fragments are present but not common except at the base of the main limestone unit, and limestone fragments are also found. Most identifiable rudists are Radiolitidae.

The pellet limestones are well sorted with an average fragment size of 0.2 to 0.5 mm. The matrix is a light-gray or cream carbonate, invariably recrystallized. It forms 30 to 50 per cent of the rock in most cases.

Pellets have been described by several authors (Hatch, Rastall, and Black, 1938). This author believes they originate mainly as faecal pellets, with possible minor contributions from rounded mollusk or algal fragments. Inasmuch as mollusk fragments commonly show some structure or regularity and pellets showing structures have not been observed, the author believes that only a small fraction of the pellets have a fragmental origin. Also, pellets tend to occur in large numbers, showing no intermediate forms to clearly defined mollusk fragments.

Andesite and sedimentary rocks.—Andesitic volcanic rock and minor conglomerate and tuff form the bulk of the San Germán formation. Good exposures occur in Barrio Llanos Tunas,

between Cabo Rojo and El Brujo. A major part of the unit is hornblende andesite porphyry. Near Cabo Rojo massive flows are abundant; to the east the rocks are more fragmental, showing fragments up to 10 to 20 cm. Basalt occurs rarely in badly weathered exposures; there are basaltic dikes on the east-west portion of Route 312 south of Cabo Rojo.

Several series ranging from tuffaceous conglomerate to calcareous lapilli tuff occur north and east of El Brujo. They are interbedded with hornblende andesite, tuffaceous wacke, rare mudstone, and 1–3-m beds of Cotui-type limestone. The conglomerate lenses are not thicker than 6 m and most are less than 3 m thick. T. R. Slodowski (1956, unpub. Ph.D. thesis, Princeton Univ., p. 35) describes the same lithologies southeast of Sabana Grande in the Susúa basin:

"Tops of flows can occasionally be distinguished by the presence of overlying volcanic conglomerate and sandstone derived from them. The succeeding flow may include subangular to subrounded volcanic and limestone fragments, giving it a conglomeratic appearance. . . . Limestone lenses between flows are not uncommon. They are massive and of small lateral extent."

Age determinations indicate that some of the pebbles and boulders in the conglomerate are probably from the Mayagüez group; others are probably contemporaneous volcanic rocks.

HORNBLENDE ANDESITE PORPHYRY: The groundmass, commonly altered to chlorite or calcite, contains varied proportions of altered ?glass, small crystals of hornblende and plagioclase, and minor magnetite, apatite, and augite grains. The specimens range from blue to lavender and red. Phenocrysts form 15–30 per cent of this porphyry, consisting of plagioclase (10–25 per cent), amphibole (5 per cent), and rare quartz, pyroxene, and biotite. Plagioclase occurs as twinned and zoned laths averaging 1–2 mm long, commonly partially altered to chlorite, calcite, or sericite. The composition of plagioclase samples from three rock specimens was determined to be sodic labradorite (An_{50-52}). Amphibole occurs as euhedral crystals averaging 1–2 mm, although 5-mm crystals are not rare. Uncommon fresh crystals are green hornblende; most crystals are altered to magnetite and hematite. Calcite and chlorite form pseudomorphs after ?pyroxene, and biotite occurs as warped corroded grains poikilitically enclosing feldspar; rare quartz fragments are found.

Contact relationships.—The San Germán formation forms a broad synclinal arc trending east-west and concave to the south (Fig. 4; Pl. 1). The formation thins from the west to a minimum in the Lajas area (0 to 100 m) and thickens farther east in the Susúa basin. The volcanic member is absent east of Lajas; conglomerates and massive limestone form most of the formation here. Gravity-slide blocks are common and with the common conglomerates and detrital limestones indicate that the Lajas area may have been higher than surrounding regions possessing a thick sequence of San Germán rocks.

The San Germán formation probably unconformably overlies the Mayagüez group and is overlain conformably by the Jicara formation. The lower contact is shown on Plate 1 near El Brujo and in the Lajas area, but the actual contact is nowhere exposed. In the region of Lajas and Route 118 and as far eastward as Sabana Grande, isolated patches of the San Germán formation overlie the older rocks. These patches of massive limestone and conglomerate in most cases cap hills in the region. The end of continuous exposure of the San Germán is not accurately known because the volcanic rocks that constitute a major part of both the Mayagüez and San Germán units are here indistinguishable. The regional structure of the Mayagüez group in the Tea syncline implies that the older volcanic unit dips steeply and strikes west or west-southwest, whereas the conglomerates and limestone of the younger units seem to be a thin blanket, with gently dipping massive rocks surrounded by variably dipping conglomerates and other rocks.

No units overlie the San Germán formation in the Mayagüez area. The Jicara formation (Paleocene) and younger rocks occur in the area but not near the San Germán exposures. Relationships in the Yauco area (Fig. 4) indicate that the San Germán and Jicara are folded in the same structure, and no evidence of discordance between them exists. Above the Jicara or (probably) above the ?Eocene is an angular unconformity.

Paleontology and age.—Most fossils in the San Germán formation are in the Cotui limestone member, both in the massive beds near the top of the formation and in the smaller limestone lenses. Limestone pebbles occur in conglomerate and tuff scattered through the formation. The commonest fossils in the formation, aside from those in the derived pebbles, are benthonic larger Foraminifera and rudists; some fragments of gastropods were seen.

The foraminiferal age determinations give a Campanian to Maestrichtian range. Two sam-

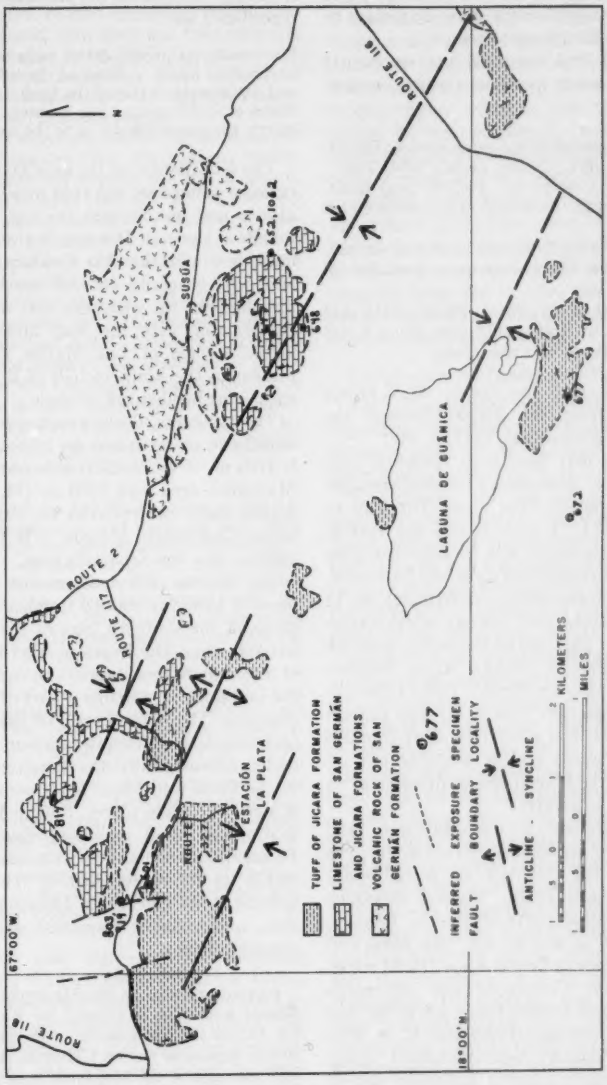

FIGURE 4.—EXPOSURES OF THE SAN GERMÁN AND JICARA FORMATIONS IN THE VALLE DE LAJAS NEAR SUSÚA

ples, however, are restricted to the late Maestrichtian (PR814, PR2732).

Samples of pebbles (PR 2055, 2120, 2124, 2132) from conglomerates give Turonian to Campanian or Campanian ages.

L. J. Chubb has identified various rudists from the formation (personal communication, 1956):

Radiolitidae, probably the same species: PR373, 443, 506, 2135, 2891 (Rosario block), 2894, 2906

Hippurites (*Vaccinites*) sp.: PR2110 (near southeast edge of large limestone area southwest of Cabo Rojo)

Durania sp.: PR505 (cobble in breccia or conglomerate above Cotui limestone southeast of Cabo Rojo)

Barrettia, near *B. monilifera:* PR427, 2133 (427 is southeast of El Brujo, 2133 float above Cotui limestone southeast of Cabo Rojo)

Durania sp. and the family Radiolitidae both extend from the Albian through the Maestrichtian (Neaverson, 1955, p. 546).

Many fossils may have been reworked from older formations. *Barrettia* is a possible example; it has been reported from upper Turonian to Campanian by L. J. Chubb and the author. Reworked fossils might also be expected from the presence of conglomerates in the formation. The two late Maestrichtian determinations in the Cotui limestone limit the age of the formation: the upper part of the formation must be late Maestrichtian or younger if the determinations and ranges are correct. One of the late Maestrichtian samples (PR 2732) may contain reworked fossils; the other (PR 814) contains abundant specimens and is probably not reworked. An early Maestrichtian determination (2738) may be reworked.

As the formation is post-Mayagüez and probably above an angular unconformity, the lower parts of the formation are probably not older than Maestrichtian. Massive limestone is present in other parts of Puerto Rico, in the Yauco area as well as near San Juan, and northeast and east of Ponce. Kaye (1956) recognizes both late Cretaceous and Paleocene massive and thick-bedded limestone in the San Juan area, and Hodge (1920) and E. A. Pessagno, Jr., (Personal communication) recognize early Tertiary massive limestone east of Ponce.

Río Blanco Formation

General statement.—Hubbard (1923, p. 26–27) uses the term Río Blanco for the volcanic rocks extending from Aguada to the southeast through Las Marías. The formation is named from exposures along the Río Blanco. Hubbard describes it as

"... made up principally of tuffs with intrusives and surface flows.... Most of the tuffs are massive and structureless, though in fresh exposures faint traces of bedding can often be seen. Here, as elsewhere, the prevailing dip is to the southwest."

The Río Blanco, as far as is known, contains massive tuffaceous volcanic rock with tongues of lava and breccia near the top, bottom, and middle of the unit. It occurs between the Yauco mudstone and the Río Culebrinas map unit and dips generally 60°–70° southwest. While it is massive, the attitudes that are found are conformable with the map units above and below. Lenses of Las Marías limestone are present in the southern half of the unit, along with some bedded tuff or shale.

The thickness, if one assumes a uniform dip of 60° and no repetition by folding or faulting, is 4700 m, of which 2700 m is measured in the Mayagüez area and 1200 m (M. D. Turner, unpub. paper presented at 1st Caribbean Geological Conference, Antigua, B.W.I., December, 1955) in the San Sebastián area.

Las Marías limestone member.—Lenses of massive hematite-stained fragmental limestone occur in the southern part of the Río Blanco outcrop area. The lenses parallel the attitudes of the Río Blanco formation, indicating that the limestone is probably a part of the volcanic sequence. The reddish stain on the limestone is probably derived from the surrounding volcanic rocks. Lithologically the limestone is similar to the Cotui and Brujo limestones except that it is red or pink in places. Fragments of rudists, gastropods, other mollusks, algae, and large Foraminifera constitute with limestone fragments up to 40 per cent of the rock; some specimens are calcilutite. Limestone breccia is seen, and volcanic fragments are present in some specimens.

MAYAGÜEZ AREA: In the Mayagüez area the Río Blanco formation is exposed on Route 119 from km 19.3 to the north border of the area (km 23.8). Better exposures are on Carretera Anoñes, Route 406, and east of the Mayagüez area on Route 120 from km 4.9 northward. All outcrops are severely weathered; the resulting clays show various shades of red, purple, and violet. Different colors distinguish different parts of the formation: purple and violet clays are exposed near the southern contact and near Las Marías, just north of the northeast corner of the area; these are separated by a belt of

red clay. The red clay in many cases has a tuffaceous appearance and the purple-violet clay a brecciated or amygdular aspect.

Breccia seems to be most common at the southern contact of the unit, with flows and tuffs becoming more common to the north. The rocks are andesitic and basaltic with amygdular flows. Breccia of feldspathic pyroxene andesite tuff fragments marks the exposures south of Las Marías.

A shale lens surrounds the northernmost lens of Las Marías limestone. Near the southern contact of the Río Blanco the attitude of a lens of fine- to medium-grained bedded tuff (N. 67° W.; 69° S.) parallels the regional attitude in the Yauco mudstone to the south. The southern contact of the unit can be traced southeast of Las Marías as a ridge in basal Yauco mudstone.

SAN SEBASTIÁN AREA: M. D. Turner (unpub. paper presented at 1st Caribbean Geological Conference, Antiqua, B.W.I., December, 1955) has mapped an area south of San Sebastián in detail, largely in the Río Culebrinas formation which is geographically north of and seemingly stratigraphically below the Río Blanco volcanic rocks. He notes as follows (in the present paper, "agglomerates" would be termed "breccias"):

"That part of the Río Blanco series mapped in the San Sebastián area was made up of a thick series of purple-brown colored, massive volcanics... (to the north) with red-, orange-, and gray-weathering massive volcanics above. Thin series of bedded volcanic sediments occur interbedded with the volcanics, especially ... (to the south). Some of the purple-brown volcanics and agglomerates give the appearance of having been vesicular basalts.... The rest of the rocks of the Río Blanco seem to be andesites very similar to some of the rock types present as fragments in the... Río Culebrinas agglomerates. Thin beds with a lateral extent of several kilometers are present in the purple-brown volcanics, but the other units of the Río Blanco tend to be much thicker and to have much less lateral extent as if they were the result of lava flows piling up near a vent. No such vent or volcanic center was found in the mapping....

"The ... contact of the Río Blanco with the Río Culebrinas is conformable. To the east of highway 119... units of the Río Blanco interfinger with units of the Río Culebrinas...."

Paleontology and age.—T. R. Slodowski (1956, unpub. Ph.D. Thesis, Princeton Univ., p. 83) lists three rock specimens from the Las Marías limestone member from Route 120 east of the Mayagüez area. These contain only *Sulcoperculina spp.* and are dated by Paul Bronnimann as "Late Cretaceous: ?Campanian to Maestrichtian." One other rock specimen (PR 2835) from the quarry south of Las Marías on Route 120 contains *S. aff. S. vermunti* and *S. aff. S. dickersoni* and is dated by Bronnimann as "Late Cretaceous: Campanian to Maestrichtian." These determinations agree on a Campanian to Maestrichtian age for the formation but do not permit correlation with other formations in the Mayagüez area.

Contact relationships.—The contact of the Yauco mudstone and the Río Blanco formation is roughly parallel to the bedding in both units. The structural position of the Yauco mudstone in this region indicates that the Río Blanco should be stratigraphically below the Yauco if the two units are conformable. Age determinations show, however, that the Río Blanco is equivalent to or younger than the Yauco. If the Yauco is in fault contact with the Río Blanco the age relationships may be satisfied, but there is no evidence of faulting. More field mapping is needed to solve this problem; with present knowledge a fault must be assumed between the two formations.

Undifferentiated ?Cretaceous Volcanic Rocks

The stratigraphic relationships of several exposures of volcanic rocks and minor sedimentary rocks in the Mayagüez area are indeterminate (unit Kv, Pl. 1).

Fine-grained tuff or andesite with some breccia is found within the Bermeja complex. These rocks are deeply weathered near San Germán and less weathered in the Sierra Bermeja. Although probably of Cretaceous age, the rocks are in general not similar to volcanic rocks of the Mayagüez or San Germán units.

South of Cabo Rojo there is a large area of vesicular and amygdular andesite porphyry and andesite breccia, not similar to the distinctive gray and reddish-gray hornblende andesite porphyry of the San Germán formation. The rocks are probably stratigraphically below the lowest-known San Germán formation outcrops in the region (the Cabo Rojo agglomerate) but still may be correlated with the San Germán. Several small areas of chert have been included in the southern part.

The areas marked Kv on Plate 1 west and southwest of Cabo Rojo and north of the San Germán fault are almost completely silicified, and the original rock is in most cases indeterminable. The southern two exposures are of hard microcrystalline chert, and the northern exposures are partly chert and partly a porous reddish siliceous rock. The latter resembles the silicified basal portions of the Mayagüez group and may have the same origin and lithologic composition (mudstone).

Jicara Formation

T. R. Slodowski (1956, unpub. Ph.D. thesis, Princeton Univ., p. 93) defines the Jicara

formation as: "composed of thin- to thick-bedded, fine-grained, siliceous and calcareous tuffs. Massive limestone and a massive volcanic conglomerate are locally present at the base of the formation." Its type locality is the region around Estación La Plata and the intersection of routes 117 and 327, about 2 km east of the Mayagüez area, southeast of San Germán (Figs. 1, 4). The formation is well described by Slodowski, who gives an age of late Paleocene and a minimum thickness of 1000 m.

The only exposures in the Mayagüez area are southeast of San Germán. The basal limestone unit trends eastward; attitudes in the tuff show a synclinal structure with an axis that trends N. 60° W. and plunges southeast. The syncline crosses the Valle de Lajas diagonally, crosses Laguna de Guánica and its long axis, and, according to Slodowski (p. 98), passes beneath the upper Tertiary coastal plain sediments.

The Jicara formation in the Mayagüez area rests unconformably upon the Mayagüez group. The contact of the Jicara is traced by means of the basal limestone member.

The San Germán and Jicara formations form a structural unit south of Sabana Grande, the only area where they occur together. If mapped as a single unit in that region, the two show a simple structure of two open synclines separated by an anticline, all trending about N. 60° W. (Fig. 4).

The depositional environment of the Jicara formation, according to Slodowski (p. 101) is a shallow basin (or basins) with calcareous debris entering from the edges and tuff blown in from nearby volcanoes. Continued subsidence permitted deposition of a thick sequence of shallow-water (?) deposits.

Slodowski (p. 99–100) listed several age determinations as a basis for the Paleocene age of the Jicara (identifications made by persons listed in parentheses):

PR601 (Bronnimann): *Globigerina* spp., rotaliids, algae (*Cymopolia* ? or *Broeckella* ?). Upper Cretaceous or Paleocene

PR647, 648 (Bronnimann): *Textularia sp.*, nondescript organic remains. Upper Cretaceous or Paleocene

PR677 (Cole): *Sulcoperculina dickersoni vermunti* (Thaidens). Cretaceous

PR803 (Pessagno): *Globigerina stainforthi, G. soldadoensis, G. triloculinoides, G.* cf. *G. pseudobulloides, Globorotalia wilcoxensis* var. *acuta, Guembelina* sp. (reworked Cretaceous form). Upper Paleocene showing slight reworking of Cretaceous

PR803 (Bronnimann): casts of *Globigerina* spp., *Globorotalia* spp., *Globigerina pseudobulloides, Globorotalia* cf. *G. wilcoxensis, Globigerina soldadoensis, crassata* type. Paleocene, but not lowest Paleocene, or slightly younger

PR919 (Pessagno): *Globorotalia compressa, Globigerina soldadoensis, G.* spp., *Textularia* sp. Upper Paleocene

?Eocene Rocks

One lower Eocene (?) locality was sampled in the Mayagüez area (PR2273); it is a marly exposure southeast of San Germán south of Route 117 (10.1 cm west, 16.4 cm north of southeast corner of San Germán 1:30,000 topographic quadrangle). The outcrop is a shallow cut a few meters long on an exposure of massive Melones limestone. Limestone cobbles are present in the marl. Several other marl outcrops nearby were sampled, but none gave ages younger than Campanian.

The region is structurally complex. The outcrop is probably an isolated remnant of a small ?Eocene basin. T. R. Slodowski (1956, unpub. Ph.D. thesis, Princeton, Univ., p. 102–105) also finds ?Eocene in the Yauco area, but his exposure is "... an outcrop of contorted, vertically dipping limestones and chalky clays ... less than 50 meters long ... probably ... a block in a fault zone." The Mayagüez area outcrop shows no evidence of faulting or of lithified Eocene sediments. Other localities of possible Eocene age are mentioned by Kaye (1956, p. 111–113), Hodge (1920, p. 193–194), and Semmes (1919, p. 74–75).

Three early or middle Eocene age determinations have been made recently by Paul Bronnimann (Personal communication), two in the Río Culebrinas formation and one in the Río Yauco series of Hubbard (1923), all three from north of the Mayagüez area. Their stratigraphic significance is discussed under Regional Geology. They are as follows:

PR2880: Río Culebrinas formation. Central La Plata quadrangle, Route 109 at a bend in the road about 160 m south of a 127.3-m benchmark, about 370 m west of the quadrangle border. Fauna: *Discocyclina sp., Proporocyclina aff. P. mirandona.* Stratigraphic determination: Eocene

PR2881: uppermost Río Culebrinas formation, San Sebastián quadrangle, Route 119, km 35.1, Escuela Gúacio. Fauna: *Truncorotalia spp., Globigerina spp.* Stratigraphic determination: lower to middle Eocene

PR2904: probably in the Río Yauco series of Hubbard (1923), Rincón 1:30,000 topographic quadrangle, Barrio Piedras Blancas, between routes 411 and 416, 7.15 cm south, 19.7 cm west of

northeast corner of quadrangle. Fauna: Tertiary *Globigerinas*, *?Truncorotalias*, reworked upper Cretaceous forms. Stratigraphic determination: lower to middle Eocene

Samples from the ?Eocene localities given by T. R. Slodowski (1956, unpub. Ph.D. thesis, Princeton Univ., p. 102–103) are as follows (identifications made by persons listed in parenthesis):

PR1062 (J. W. Wells): *Leptoria* (*Dictuophyllia*) *conferticostata* Vaughan, *Multicolumnastrea cyathiformas* (Duncan), *Cladocora jamaicensis* Vaughan. Upper Cretaceous of Jamaica and Mexico

PR652 (Bronnimann): *Nonion* sp., *Globorotalites michelinianа*, *Kathina jamaiensis* (common), *Sulcoperculina* sp., *S.* cf. *S. vermunti*, *Nonionella cretacea*, *N. robusta*, *Quinqueloculina* sp., miliolid, ostracods, prisms of *Inoceramus* sp., gastropods, pelecypod and echinoderm fragments. Upper Cretaceous (Campanian-Maestrichtian) or younger with reworked Upper Cretaceous

PR652 (Bolli): rich fauna of *Globorotalia* cf. *G. crassata* var. *densa*, *G.* sp., *Nonion* sp., characteristic species of a form near *Amphistegina*, numerous ostracods. Probably Eocene (? Middle lower)

PR652 (van den Bold): ostracods: *Cytheridea* A, B1, B2, C1, C2; *Cytherella* sp., *Cythereis collei* Gooch, *Paragpice* sp., *Brachycythere jessupensis*, *Bairdia* sp. Lower to middle Eocene

Middle Tertiary Rocks of the Coastal Plain

The Oligocene and Miocene sediments exposed along the south coast have been described by Berkey (1915), Hubbard (1923), G. J. Mitchell (1922), Meyerhoff (1933), and Zapp, Bergquist, and Thomas (1948). Thomas (*in* Zapp, Bergquist, and Thomas, 1948) recognizes two formations in the middle Tertiary of the south coast: these are the Juana Díaz formation ("... about 655 m of middle Oligocene conglomerate, sandy limestone, and shale") and the Ponce formation ("... of upper Oligocene and lower Miocene age ... [with] a lower unit of chalky thin- to medium-bedded limestone of a probable maximum thickness of 900 m, and an upper unit of about 400 m of hard, finely crystalline limestone.")

The Juana Díaz formation is correlated with the San Sebastían formation of the north coast, the basal unit of the northern coastal plain. Thomas maps as Juana Díaz an outcrop between the Sierra Melones and the Sierra Bermeja; it consists of soft sandy limestone dipping about 15° southward. The present author correlates an exposure south of the western Sierra Melones, an exposure about 2 km directly south of the Juana Díaz outcrop mapped by Thomas, and a series of outcrops in the Valle de Lajas, near Boqueron with the Juana Díaz formation. The first two are composed of fairly hard iron-stained impure quartz sandstone with large (up to 10 cm) red-chert fragments, probably derived from the basal (Bermeja) complex. This rock type is probably the source of the red sandy soil that gives the area and the cape the name "Cabo Rojo."

The outcrops in the Valle de Lajas are composed of a gravel exposed in vaguely distinguishable 0.6–1.0-m beds containing chert pebbles in an iron-rich red clay. The chert is red, in places leached white and made porous-appearing but still quite hard. Pebble size ranges from 1 mm to 10 cm, and pebbles are subangular to rounded. Thin streaks of gray-white clay are probably zones of reduction in the red clay.

These exposures are similar to exposures of the basal conglomerate and gravel of the San Sebastián formation of the north coast Tertiary, shown to the author by M. D. Turner and described by Turner in 1955 (unpub. paper presented at 1st Caribbean Geological Conference, Antigua, B.W.I., December, 1955). Zapp, Bergquist, and Thomas (1948) state that the San Sebastián is

"... predominantly gravel in the lower part.... The coarsest beds consist of boulders and cobbles derived from the igneous and sedimentary rocks of Cretaceous age. These are embedded in a matrix of red sandy clay.... Nearly everywhere they are characterized by very poor sorting, with all grade sizes from clay to coarse gravel and cobbles intimately intermixed."

Thomas (*in* Zapp, Bergquist, and Thomas, 1948) maps exposures on (cape) Cabo Rojo and five exposures south of the Sierra Bermeja as the upper member of the Ponce formation, a hard, pinkish-white, finely crystalline limestone. The author has correlated the three largest outcrops to the east with the upper Ponce, but the two smaller outcrops, south of the southern Juana Díaz outcrop, are part of the Juana Díaz and Parguera formations, respectively. The upper Ponce formation is also exposed on Isla Cueva and Isla Guayacán west of Parguera, on Cabo Rojo, and on Punta Aguila, 3 km northwest of (cape) Cabo Rojo.

Guanajibo Formation

McGuinness (1948, p. 30–31, p. 226–228) has found in water wells drilled in Mayagüez

"... a series of light-yellow to gray limestones, sandy or earthy, ranging from soft to fairly hard, and sands, silts, and clays. The deepest well known to end in these sediments is well Mg36, which was 256 feet [84 m] deep. The position of the top of the

Tertiary sediments in this and other wells in Mayagüez is uncertain, but it is 80 feet [26 m] or less below the surface in well Mg76 and perhaps 62 feet [20 m] or less in well Mg60.

"... Foraminifera from the lower parts of wells Mg38, 60, and 76 at Mayagüez, examined by J. A. Cushman... are... similar to forms from Buff Bay, Jamaica, which are thought to be late Miocene—or possibly Pliocene—in age.

"As the four valleys in which sediments of known or probable Tertiary age occur open up on the Guanajibo Channel [Mona Passage], the name Guanajibo formation is suggested for these sediments."

McGuinness correlates these sections with those of other wells in the Lajas, Guanajibo, and Añasco valleys which, however, are not dated. As limestone is quite close to the surface in wells in the western parts of the Lajas and Guanajibo valleys, he thinks that outcrops of the formation might be found in these valleys. R. C. Mitchell (1954, p. 58–62 and frontispiece) mentions this and shows a large area as belonging to the Guanajibo formation in the region described. This area corresponds to a gray massive fragmental limestone with rudist fragments and Campanian-Maestrichtian Foraminifera, mapped by the present author as limestone of the San Germán formation.

There are, however, valid surface exposures of the Guanajibo formation. A "yellow and white marl and sandy siltstone" (C. A. Kaye, personal communication) correlated with the Guanajibo formation is "on the north side of the Lajas valley, about one-fourth mile (0.4 km) east of the western intersection of routes 4 and 306."

San Juan Formation

On Cabo Rojo the San Juan formation, a Pleistocene dune-sand deposit originally described by Berkey (1915), caps the Ponce formation (G. J. Mitchell, 1922, p. 260–261). Thomas states (*in* Zapp, Bergquist, and Thomas, 1948): "At that locality are cross-bedded, lime-cemented dune sands overlain by a conglomerate composed chiefly of pebbles of Cretaceous rocks and containing a few Pleistocene shells." R. C. Mitchell (1954, p. 63) found the formation also on Isla Cueva and the offshore reefs near Parguera. These were not studied by the present author. The formation is grouped with the coastal-plain sediments (Tjp) on Plate 1.

Quaternary Deposits

Gravels, clays, and silts form alluvial fan, river, and possibly lake deposits in the large valleys of the Mayagüez area. These were not studied in detail; their outlines were taken from the map of Zapp, Bergquist, and Thomas (1948) and from the soil map of Roberts (1942). The main east-west valleys are the Lajas, Guanajibo, and Añasco valleys. Smaller alluvial deposits are found along the larger tributary valleys opening into the major valleys. Recent seismic work northeast of Laguna Guánica in the Yauco area has shown that the alluvium is about 20 m thick. Well logs listed by McGuiness (1948) give the following maximum depths to the first rock intersection in several valleys: 50 m in the Valle de Lajas, 30 m in the Valle de Guanajibo, 33 m in the Mayagüez Valley, 82 m in the Valle de Añasco, and 50 m on the south coast.

Intrusive Igneous Rocks

Dikes and other small intrusions are fairly common in the Mayagüez area. Most are andesitic and similar to the country rock and will not be considered further. Exposures are too poor to permit location of these bodies on Plate 1. South of Route 329 on the eastern border of the area a small plug of hornblende and pyroxene diorite intrudes the serpentinite. The plug has recrystallized the serpentinite to an olivine hornfels (granoblastic olivine and bronzite with minor poikiloblastic red-brown hornblende and biotite). Hornfels phases of the plug are also seen. T. R. Slodowski (1956, unpub. Ph.D. thesis, Princeton Univ., p. 117) has interpreted the hornfels as a mylonite, but it is not found elsewhere where faults cross the serpentinite. Another small plug, ranging from augite-quartz monzonite to augite granodiorite, cuts lava and mudstone of the Mayagüez group south of Route 105 at the eastern border of the area. The rock is silicified and silicated around the plug.

QUARTZ DIORITE PORPHYRY (PL. 2, FIG. 4; TABLE 1): Sills and dikes of quartz diorite porphyry are found on the Tea road (Route 118) as far west as Lajas and as far east as the border of the area. Two larger elongate bodies are exposed in the center of the Sierra Bermeja. The diorite and dacite commonly intrude the Mayagüez group, but north of Lajas a dacite dike cuts the Cotui limestone of the San Germán formation (?Maestrichtian).

The groundmass of the analyzed specimen is almost completely altered to chlorite, calcite, and sericite, with small plagioclase remnants, but other specimens show a mass of generally untwinned

anhedral feldspar grains 0.02–0.04 mm in size. Phenocrysts make up 25–40 per cent of the rock, consisting of plagioclase (15–25 per cent), quartz (0–8 per cent), amphibole and mica (2–13 per cent), and accessory minerals such as ?magnetite, apatite, leucoxene, and in some cases pyrite (1 per cent). Plagioclase occurs in euhedral or subhedral crystals 3–6 mm long (some are as long as 20 mm), twinned and zoned but more commonly twinned, and altered to sericite. Quartz generally forms 6–8 per cent of the rock but is absent in some exposures. Quartz grains are unaltered, rounded probably owing to resorption, and rarely in strained crystals show a biaxial interference figure ($-2V = 20°$). Grain sizes are 2–3 mm and 0.2–0.3 mm; some of the larger grains have crystal faces. Some generally euhedral green hornblende occurs as laths 0.4–1.0 mm long; it is commonly altered to chlorite, colorless mica, and perhaps leucoxene. Colorless mica, with an extinction angle of 10°–15°, also is a primary mineral in some specimens.

An alternative name for the rock is quartz micro-diorite porphyry.

VARIETY: MICA-QUARTZ DACITE PORPHYRY: In the Tea region are dikes of a light-colored rock, in many places altered to calcareous clay containing euhedral doubly terminating quartz bipyramids (6.6 per cent) and colorless mica books (2.6 per cent). The groundmass is similar to the diorite described but is more abundant (90 per cent); another difference is the scarcity of plagioclase phenocrysts (1 per cent). The plagioclase is highly altered and in many cases in clustered aggregates with quartz. The mica is pale green or colorless, with a negative 2V of 25°–30°. The rock should probably be classified as mica-quartz dacite porphyry, or perhaps latite porphyry, as the K_2O content was not determined. The dacite is probably a facies of the diorite porphyry.

STRUCTURAL GEOLOGY

General Statement

In southwestern Puerto Rico a basement complex of generally obscure origin and structure is covered by an older bedded sequence of moderately to intensely folded sedimentary and volcanic rocks and a younger bedded sequence of sedimentary rocks which has been tilted or gently folded. Unconformities separate each of these three major sequences, and an unconformity divides the older bedded sequence into two parts (Figs. 5, 6, 7). Because of wide spacing of outcrops, small features such as drag folds and cross folds are concealed. These are indicated by aberrant dips and strikes. Continuous good exposures, as on routes 4 and 118 in the Tea syncline and on Route 120 east of the northeast corner of the area reveal drag folds, cross folds, and much minor faulting (Pl. 3, fig. 2).

The lack of bedded exposures prevents detection of the structure of the basal (Bermeja) complex. The complex comprises silicified volcanic rocks and basic igneous rocks intruded (?) by serpentinized peridotite. The younger bedded sequence, post-Eocene, is monoclinal, dipping gently toward the coast. The older bedded sequence is divided into two parts. The younger, the Paleocene (Jicara)-Eocene and the ?Maestrichtian (San Germán), occurs in simple open synclines, not usually tightly folded. Both together form a large arc concave to the south, stretching from Punta Guanaquilla into the Yauco area, disappearing beneath the Oligocene-Miocene sedimentary rocks south of Yauco. The structure is exposed continuously west of Lajas; to the east it exists as isolated outcrops. An exposure near Rosario is interpreted as an anticlinal crest, detached from its original site (to the south), and it probably slumped or slid onto older rocks.

The Mayagüez group and the Río Loco formation are exposed in the Vertero, Melones-Tea, Hormigueros, and Las Vegas synclines and the Parguera anticline.

Most folds of the older bedded sequence are overturned or asymmetric. The degree of asymmetry increases from north to south and in most cases involves the north limbs of the synclinal folds. The northern limbs of the Las Vegas and Hormigueros synclines dip an average of 20°–30° more steeply than the south limbs, and overturning and overthrusting are found locally in the Hormigueros syncline. The north limb of the Tea syncline dips steeply or is overturned, and the Melones syncline is isoclinally overturned to the south. The Parguera anticline, however, is overturned and thrust to the north. The general trend of the older bedded sequence is N. 60° W. In the extreme southwest, however, the folds arc to the southwest. This deviation is perhaps the result of trends in the basement affecting orogenic forces that caused the folds.

The outcrop patterns of the various units and the abundant attitudes on Plate 1 outline the folds. The overturning and asymmetry of the northern limbs of the synclines may be most easily picked out by reference to attitudes on Plate 1. Only in a few cases was overturning determined by graded bedding or other top-bottom features. Graded bedding is well exposed in the upper tongue of the Yauco mudstone along Route 118 and in the conglomerate lenses west of the road, the latter lenses resting upon the lower Yauco mudstone

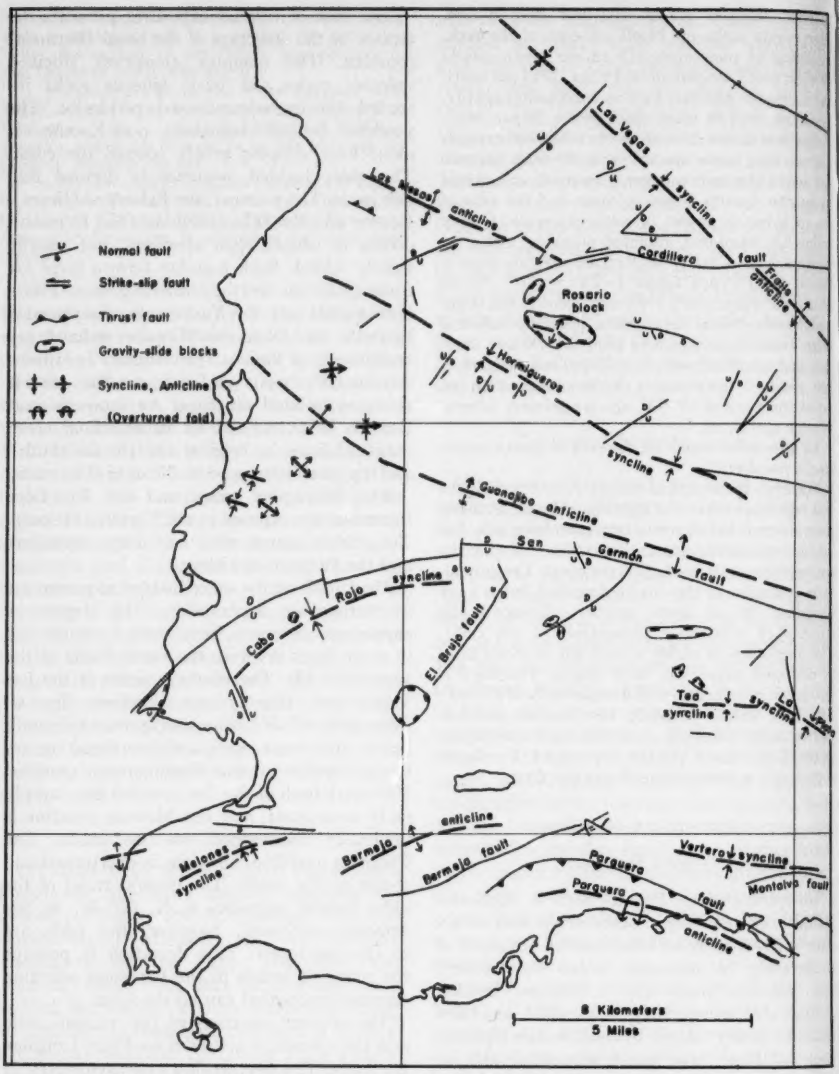

FIGURE 5.—STRUCTURE OF THE MAYAGÜEZ AREA

tongue. Overturning of the eastern part of the Tea syncline is graphically shown along Route 118, where the dips range from 60° to 80° S. to 90° and 85° N. from north to south, all in the upper tongue of the Yauco mudstone.

The Las Mesas-Fraile anticline is in some places thrust to the south over the Hormigueros syncline. This movement is localized at the Bermeja-Río Loco contact and perhaps also at the Río Loco-Mayagüez contact. On a dirt road connecting Routes 348 and 349 near Mayagüez, the contact of the Bermeja complex and the Río Loco formation dips north, and mudstones in the Río Loco near the contact are shattered and probably sheared. The serpentinite is foliated parallel to the contact. Elsewhere the contact is also overturned, and near

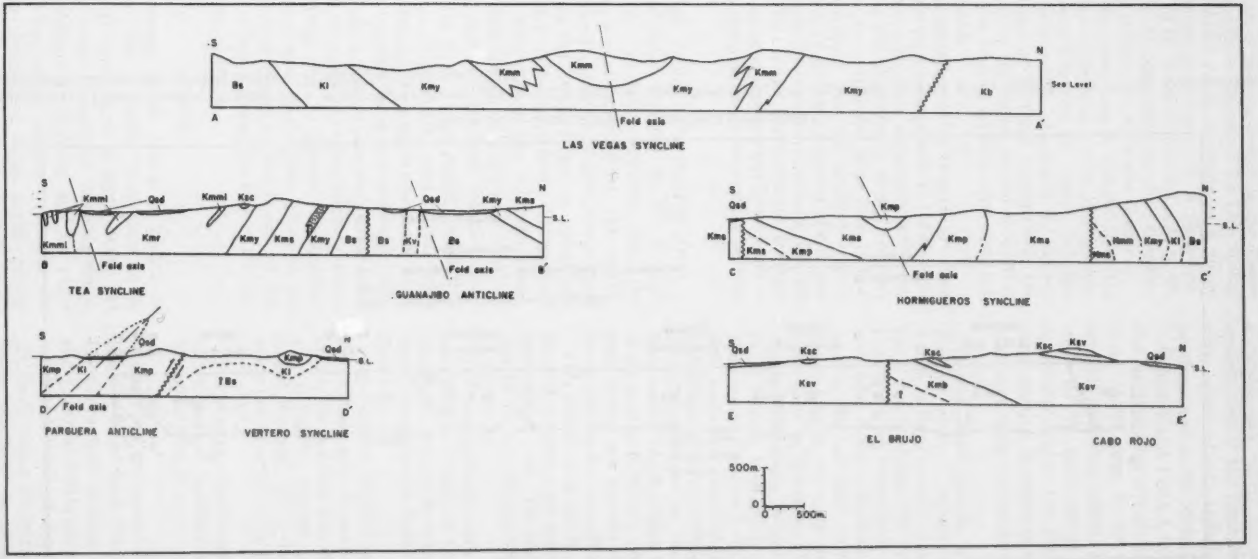

FIGURE 6.—STRUCTURE SECTIONS

Sharp wavy lines show faults. Alluvium = Qsd. San Germán formation = Ksv; Cotui limestone member = Ksc. Mayagüez group—Brujo limestone = Kmb; El Rayo volcanic rocks = Kmr; Maricao basalt = Kmm; Melones limestone = Kmml; Parguera limestone = Kmp; Sabana Grande andesite = Kms; Yauco mudstone = Kmy. Río Loco formation = Kl. Bermeja complex = Bs.

FIGURE 7.—GENERALIZED STRUCTURE SECTION

Sharp wavy lines = faults; straight lines = normal contacts; gentle wavy lines = unconformities; dot-dash lines = fold axes; dotted lines = the continuation of structures above the present surface. Dashed lines indicate doubt.

Route 120 north of Sabana Grande in the Yauco area there is an isolated exposure of Río Loco resting upon the Mayagüez group, probably as a klippe thrust upon the younger rocks (*cf.* T. R. Slodowski, 1956, unpub. Ph.D. thesis, Princeton Univ., p. 58, 118-119, Pls. 1, 2). Slodowski also finds thrusting along the same contact east of Sabana Grande.

In other cases overturning is deduced from the over-all structure of the area. In the Melones syncline the Melones formation has closure, but dips are generally northward in all parts of the outcrop area. Paleontological evidence demonstrates the synclinal nature of the region. It also shows that the Parguera hills form an anticline overturned and thrust to the north.

The northern exposures of the Parguera limestone in the Hormigueros syncline, chiefly in the east and central portions, also show asymmetry and overturning. This is well illustrated by several traverses across the structure. Attitudes range from vertical or northward-dipping near the northern contact through vertical to southward-dipping as one proceeds to the south. The southern limb has an average dip of 40°, whereas the northern limb averages 60°-70°. The same asymmetry has been found in the Las Vegas syncline, but no overturning has been found there.

Deformation could have resulted from a compressional force oriented N. 30° E. The asymmetry of the folds indicates that the deformation was directed from the north-northeast. The Parguera anticline, overturned and thrust to the north, forms an exception. This and other departures from the regional orientations occurring in the southern structures may result from a deforming force acting on the thin edges of the thick sediment lens. The sediments at the edge might be affected by basement alignments, and form folds oriented differently than those elsewhere. Also, in such a situation forces not ordinarily predominant might influence relatively thin bodies of sediment in seemingly contradictory ways. Thus, slumping due to gravity or another locally directed force might have acted on the thin sedimentary layers in the region of the Parguera anticline, causing the fold to deviate from the regional trend.

Faults

Every outcrop shows joints or planes of displacement, but generally these seem to be minor. Actual fault planes of larger faults are rarely seen; where structural evidence necessitates a solution by faulting and no other evidence of large-scale faulting is seen in the field trends determined from aerial photographs are used, and a probable fault is drawn in. Since fault planes are not usually seen, their attitudes can rarely be measured; from the straightness of the fault traces most are probably quite steep, especially in the rugged northern and north-central regions.

Figure 5 and Plate 1 indicated that most of the faults are transverse to the fold axes in the area. There seem to be three sets, one (the largest) trending about N. 45° E., another at N. 20° W., and a set of east-west left-lateral strike-slip faults. On Plate 1 in most cases their relative movements are shown; they may also have other less evident components.

Several faults contain gouge or are foliated. Foliated marble is exposed on Route 118, at the Yauco-El Rayo contact. It is parallel to bedding in the Yauco (east-west; 80° N.) and is probably the trace of a steep reverse fault, a bedding-plane fault. This fault seems to be offset by a north-northeast fault to the east, and, farther to the east in the Yauco area at the same stratigraphic position, a thrust fault is picked up (T. R. Slodowski, 1956, unpub. Ph.D. thesis, Princeton Univ., Figs. 11, 12, Pl. 1) dipping from gently to steeply northward. This may be the same fault; stratigraphic displacement cannot be measured in either portion. They perhaps are essentially bedding-plane faults, created during the folding of the Tea syncline by differential movement of the Mayagüez strata. The eastern end of the fault in the Yauco area turns northward and ends at the San Germán fault, probably cutting across bedding in this northward-trending portion.

Five meters of gouge in a low hill of chert or silicified volcanic rocks occur in the Valle de Lajas southeast of Lajas. The fault strikes east-west and dips 70° S., but the direction of motion could not be determined.

The Bermeja fault, south of the Sierra Bermeja, is marked by a zone of foliated serpentinite with calcite alteration. It is vertical; this could be due to later folding, as the fault is entirely in the basal complex.

The Parguera fault follows the northern side of the Parguera hills. It was not seen in the field; the beds in the northern limb of the Parguera anticline are overturned, however (according to paleontological evidence), and a thrust fault must exist to relate this structure to the structure of the rocks to the north.

The Montalva fault, marked by a zone of silicification, has no measurable displacement in the Mayagüez area.

The most prominent faults in the area are the Cordillera and Sam Germán faults. The Cordillera fault crosses the northern part of the Yauco and Mayagüez map areas and ends north of Rosario. It is a transcurrent or strike-slip fault with a left-lateral sense. Displacement along the fault decreases from east to west. In the Yauco area the Río Blanco-Yauco

contact is displaced about 14 km, and the Las Mesas anticlinal axis farther west is displaced an estimated 6 km. Near the western end of the fault the contact of the southern serpentinite and the Río Loco is displaced only about 1 km. From Rosario westward, part of the movement is taken up by another parallel transcurrent fault and perhaps also by thrust faulting along the contact between the serpentinite and the Río Loco.

The San Germán fault crosses the entire area and disappears in the serpentinite east of Sabana Grande, for most of the distance paralleling the San Germán-Jicara formation trends. A scarp marks the fault line along the south side of the Valle de Guanajibo. Its length and orientation parallel to the Cordillera fault suggest that it is also a transcurrent fault, and T. R. Slodowski (1956, unpub. Ph.D. thesis, Princeton, Univ., p. 117) has postulated a left-lateral movement thrusting the Mayagüez group beneath the serpentinite east of Sabana Grande.

The straight northern border of the Valle de Guanajibo also suggests a fault, but little evidence supports this. The same can be said of the borders of the Valle de Lajas, where there is some evidence of faulting.

Strike-slip faults of great length and large displacement (up to 33 km) are described by Rod (1956) along the southern border of the Caribbean in Venezuela, Colombia, and Trinidad. These are right-lateral in sense, implying, as does the Cordillera fault, that the Caribbean area has moved eastward relative to its borders. Hess and Maxwell (1953) have postulated large left-lateral strike-slip faults along the northern border of the Caribbean.

The different fault sets (N. 45° E., N. 20° W., E-W) seem to be roughly contemporaneous, as faults of each set offset faults of other sets. A transverse fault cuts the Paleocene Jicara formation, so some faulting is post-Paleocene; a N. 75° E. fault is reported by Zapp, Bergquist, and Thomas (1948) to cut the Ponce formation of Oligocene-Miocene age south of Yauco. Probably most of the faulting is connected with the late Cretaceous and early Tertiary foldings, but some has continued to the present; several earthquake epicenters have been located off the coast of western Puerto Rico, and Moneymaker (1947, p. 1211) has reported probable active faults crossed by tunnels in central Puerto Rico. The Bermeja fault may date from an older deformation, as it is entirely within the older complex and is more highly foliated than other faults.

Several faults are marked by zones of silicification; these are shown on Plate 1.

Gravity-Slide Blocks in the San Germán Formation

At the base and scattered through the San Germán formation are highly contorted sedimentary rocks of different ages. Most of the exposures are surrounded by volcanic rocks which show no structural similarity to the bedded rocks and which are of different ages than the bedded rocks. These bedded exposures are considered allochthonous blocks, moved by landsliding or submarine slumping. The slides seem to have occurred at several times, as blocks occur at the base of the San Germán formation near Lajas and near the top of the same formation southwest of Cabo Rojo. One block near Rosario involves the formation itself. Most of the exposures are shown on Plate 1, but several outcrops near Lajas are too small to be shown. They can be located by sample numbers (PR2263–2265) on Plate 1.

About 1 km south of Rosario the San Germán formation occurs as large thick lenses of microcoquina and pellet limestone and as exposures of medium-bedded tuffaceous mudstone, siltstone, and conglomerate. E. A. Pessagno, Jr. (Personal communication) noted microslump structures and deformation of the Foraminifera in a sample of the mudstone of this block (PR2738). Pessagno also found biotite flakes in the sample; biotite is common in the area only in the San Germán formation andesite. Attitudes in the bedded material parallel the borders of the massive limestone lenses, and they are considered indicative of a steeply dipping anticline plunging steeply to the east. The whole series of exposures forms a roughly triangular area surrounded by volcanic rock of the Mayagüez group. For convenience, the series of outcrops is referred to as the Rosario block. Paul Bronnimann has dated the southern limestone bed of the block (2732) as late Maestrichtian. A determination by Pessagno of early Maestrichtian (2837) contradicts this; the latter age is believed to be from reworked older beds in the block.

The Rosario block cannot be considered part of the surrounding Mayagüez group, as it is lithologically and structurally distinct. It cannot be a fenster, as it is younger than the surrounding rocks. There is no evidence against a thrust-sheet origin for the Rosario block; however, its limited lateral extent is not characteristic of far-traveled thrust sheets and implies a gravity-slide origin.

A small area of Río Loco lavas and Yauco mudstones west of Rosario is also considered an allochthonous block because of its shape and lack of correlation with surrounding rocks.

The other blocks are in the synclinal arc of the San Germán formation. Lithologically they are similar to the Mayagüez group, composed of roughly 35 per cent calcilutite, much of which is weathered to marl, 30 per cent mudstone similar to Yauco mudstone, 15 per cent conglomerate, arenite, calcarenite, and fragmental limestone, and 20 per cent volcanic rock, mostly breccia and volcanic conglomerate. The blocks range from very small to 2 km by 0.5 to 1.0 km.

Foraminiferal age determinations in these latter blocks range from early Campanian to early Maestrichtian. One of the younger samples (2121) shows reworking. Inoceramids from an area tentatively included in one of the blocks (PR393) "... appear to be most closely related to the *Inoceramus deformis* Meek group which is typical of the Coniacian (Austin age) of the Gulf Coast and the Western Interior" (J. B. Reeside, *in* N. F. Sohl, 1956, unpub. report). An echinoderm found as float in the block south of El Brujo (PR2100, C. W. Cooke, 1956, unpub. report) is described as *Conulus* sp. and dated (?)Campanian. E. A. Pessagno, Jr. (1955, unpub. ms., Princeton Univ.), speaking of specimens from two different blocks north of Lajas, says:

"... many of the microfossils have been flattened, stretched, and crushed. Most of the flattening and certainly the crushing may be due to compaction from [the weight of] overlying sediments. However, a certain amount of elongation and stretching does occur; not all of this can be explained by compaction alone."

These exposures are extremely contorted. Good exposures near the north end of Route 316 show more or less horizontal beds of tan glauconitic calcilutite in a small recumbent fold above beds of the same composition dipping steeply southwards. Beds in the elongate patch northeast of Lajas form a tight fold with closure at both ends; these beds are steeply dipping mudstone and calcilutute. Several isolated circular hills expose crumpled beds, in most cases steeply dipping.

These exposures can be interpreted in several ways: (1) they may be the basement below the surrounding rocks, exposed in fensters; (2) they may be bedded facies of the surrounding rocks and hence contemporaneous with them; (3) they may be remnants of a thrust sheet or thrust sheets; (4) they may be the products of landslide or slump of older rocks into a younger depositional environment. The first two hypotheses may be quickly eliminated. Age determinations show that the exposures are in general older than the surrounding rocks, and the structure and thickness of the Tea and Hormigueros synclines indicate that the exposures are probably not fensters. Also, there is no evidence of any strong contortion in the San Germán volcanic rocks and limestones that surround most of the exposures.

As the blocks are at different stratigraphic levels and are of different ages and lithologies, several large thrust sheets containing several different formations must be postulated in the thrust-sheet hypothesis. Because of this and because of the limited lateral extent of the exposures the thrust-sheet hypothesis is discarded in favor of the gravity-slide hypothesis.

If these exposures result from gravity sliding or slumping, there must be a slope down which they moved. Probably the slope was near the greatest concentration of slide blocks, in the Lajas region. The Lajas region has already been mentioned as a possible high region, because the San Germán formation there is thin and discontinuous. The blocks contain elements of both the Parguera and Yauco lithologies, implying a source somewhere in this area also, where the autochthonous Mayagüez group has a similar group of intermediate lithologies. One can postulate landslides on a fault scarp in the Lajas-San Germán region, but there is no evidence to substantiate this.

Intense local contortion of the thin bedded rocks indicates that the beds may have been relatively unconsolidated when they slid and were deformed; otherwise they should have been brecciated to some extent. Deformation of the Foraminifera, however, implies that the matrix of the rocks was rigid enough to exert nonhydrostatic pressure on the foraminiferal tests during the deformation. The Mayagüez group was folded and large parts were eroded away before the sliding occurred; it would be surprising if some consolidation had not taken place. The matrix, then, was probably partly consolidated, enough to deform the Foraminifera but not enough to cause much fracturing or brecciation during the slide.

Submarine slide breccias and slide blocks have been described by many authors (Kugler, 1939; 1953; Bailey, Collet, and Field 1928; Renz *et al.*, 1955), and de Sitter (1956, p. 266–291) gives an excellent summary of the problem.

The sliding of the blocks near Lajas and San Germán took place during San Germán time, as San Germán rocks partly cover the slide blocks in that region. The only alternative

is to consider all the San Germán outcrops on the Mayagüez group as allochthonous slide blocks. The time of movement of the Rosario block, however, is not definitely known, because it involves the San Germán formation itself and is not overlain by other rocks. The sliding of the Rosario block, then, can only be dated as Maestrichtian or younger.

Geologic History

The earliest volcanic and sedimentary cycle is represented in southwestern Puerto Rico by the Bermeja complex. Serpentinite, porphyritic volcanic rocks, and fine-grained volcanic or sedimentary rocks were formed, along with some spilitic flows. Amphibolites similar in chemical composition to olivine basalt occur in the southern parts of the area. The porphyries and fine-grained rocks were silicified following their formation.

The next recorded event (?Cenomanian) is the extrusion of bronzite andesite lavas. In the north these lavas apparently flowed beneath the sea and developed pillows; in the south the flows were perhaps near or above sea level. The southwesternmost parts of the area were not covered by the lavas.

Rocks of the Mayagüez group were deposited in a tropical or subtropical shallow-water area with abundant nearby volcanic activity and with some small regions of older rocks above sea level. There seem to have been two volcanic sources during Mayagüez time (Turonian (?) to Maestrichtian). One contributed andesite breccia with minor lava and tuff to the central part of the area; the other added basalt lava with minor breccia and massive tuff to the northern part of the area. There may or may not have been a physical barrier between these two regions during middle and late Mayagüez time; there was no such divide during early Mayagüez time, as the northern-type basalts are found in the central regions. Contemporaneously with the volcanic activity, a thick sequence of tuffaceous muds was deposited in the northern regions and to a lesser extent in the central regions. A small amount of detritus (largely amphibolite) eroded from pre-Mayagüez hills during early Mayagüez time was deposited along with contemporaneous volcanic debris as conglomerate lenses in the central part of the area.

In the southern part of the area rudist-rich fossil detritus and calcilutite muds formed deposits on a shallow bank or banks; the deposits contain almost no volcanic material. In the central regions, between the lime-mud and reef environment of the south and the tuffaceous-mud and lava environment of the north, both types of muds formed, their relative proportions depending upon the intensity of volcanic activity. Tuffaceous muds were more common in early Mayagüez time and lime muds predominated in late Mayagüez time in the central region.

Near the end of Mayagüez time older Mayagüez deposits were reworked before and during the formation of rudist banks. Basaltic and andesitic flows and breccias were also deposited in the central parts of the area. The reworking may have been due to uplift accompanying the folding that ended Mayagüez time.

No direct evidence of volcanic centers has been found. The source of the lava and breccia of the Las Vegas syncline is probably outside the area. The volcanic rock of the Hormigueros and Tea synclines does not extend to the south, north, or east; no directional properties have been observed in these rocks. The size of fragments in the breccia indicates a nearby source (less than a few tens of kilometers), either undetected within the area or to the west in the region now covered by the San Germán formation.

Uplift and reworking of the Mayagüez sediments was accompanied by deformation into broad folds. Erosion began immediately, for by San Germán time the Mayagüez folds were truncated.

In San Germán time (?Maestrichtian) thick andesitic volcanic rocks were deposited in shallow water or subaerially with locally derived limestone and conglomerate. The conglomerate contains some pebbles of Mayagüez age. Larger blocks of Mayagüez rocks also slid or slumped onto San Germán or autochthonous Mayagüez sediments during this time, and some were covered by more San Germán deposits. Organic detrital deposits of the same age formed thick banks in the south-central part of the map area. This type of limy deposition continued into Jicara time (Paleocene), but it is not clear if there was a break in deposition between the Jicara and the San Germán. Ash falls are the only evidence of volcanic activity during Jicara time in this area.

The post-Jicara record is fragmentary in the Mayagüez area. A large block of San Germán deposits slid or slumped northward onto

older rocks sometime after deposition of the San Germán sediments. The San Germán, Jicara (Paleocene), and older rocks were folded during the Eocene-early Oligocene interval, possibly concurrently with the intrusion of granodiorite and diorite plugs, sills, and dikes. As elsewhere on the island extensive Eocene sedimentary and volcanic rocks are folded with the older sequence; the folding was probably in the late Eocene-early Oligocene interval. Uplift and erosion followed this folding of the older bedded sequence.

Shale and conglomerate of middle Oligocene age, deposited on a surface of considerable relief, give way to marly limestone and reef limestone of Oligocene-Miocene age, deposited over large areas now forming the north and south coasts of the island. Uplift and arching ended the deposition on the north and south coasts, but the west coast seems to have been downwarped, receiving marly lime deposits in late Miocene or Pliocene time. Only warping occurred at this time, and the post-Eocene strata now dip in general less than 10°. Dune sands formed in the Pleistocene along parts of the north and west coasts of Puerto Rico; erosion with some variations in elevation, along with seismic activity, continues to the present.

Regional Geology

The Yauco area east of the Mayagüez area was mapped by T. R. Slodowski (1956, unpub. Ph.D. thesis, Princeton Univ.). It contains the same rock types as the Mayagüez area. The following is the present author's interpretation of the structure of the Yauco area:

Most of the trends in the Mayagüez area converge to the east or die out against the Las Mesas-Fraile anticline. The Hormigueros syncline shallows to the east and ends as isolated patches of Río Loco lavas on the serpentinite east of Sabana Grande. The Guanajibo anticline narrows and finally merges with the Fraile anticline. The Tea syncline passes over a saddle south of Sabana Grande and then deepens again to form the Susúa basin, which ends also against the Fraile anticline. The Vertero and Parguera structures extend north and south of Ensenada, respectively, beyond which they are buried by coastal-plain sediments. As described elsewhere, the Cabo Rojo-La Plata synclinal complex crosses the Valle de Lajas at Laguna Guánica and also disappears beneath the coastal-plain sediments.

The only structure not ending in the Yauco area is the Las Vegas-Pasto syncline, north and northeast of the northern serpentinite mass. It becomes obscure north of Yauco as the fold broadens and dips decrease. Even the trend of the fold is doubtful; it may leave the area trending anywhere from east–west to S. 30° E. Possibly more than one structure is involved.

The mudstone-volcanic lithofacies predominates north and east of the Mayagüez area. The limestone facies does not reappear in quantity until as far east as Ponce, in Cretaceous rocks, and in Eocene rocks near Coamo (E. A. Pessagno, Jr., personal communication).

M. D. Turner (unpub. paper presented at 1st Caribbean Geological Conference, Antigua, B.W.I., December, 1955) stated that to the north in the San Sebastián map area the Río Blanco formation rests conformably upon the Río Culebrinas formation, the latter composed of tuff, breccia, and minor sedimentary rock. The Río Blanco formation is ?Campanian to ?Maestrichtian by four determinations, but its relationship to the Mayagüez group has not been well established. ?Eocene age determinations have been made recently by Paul Bronnimann in the Río Culebrinas formation (Pl. 6; *see also* the section on ?Eocene rocks). So if its northern contact is conformable, the Cretaceous Río Blanco is in the anomalous position of being stratigraphically above Eocene rocks. Future mappers must distinguish structurally distinct units within the Río Blanco or reinterpret the Río Blanco contacts to solve this problem.

A tectonic synthesis of Puerto Rico must await further regional mapping (Fig. 8). The pre-Oligocene rocks of Puerto Rico are lithologically similar to the Mayagüez-Río Blanco-Río Culebrinas rocks of western Puerto Rico. The structure of the island will probably be described in terms of several large folds. The whole area southwest of and including the Las Mesas-Fraile anticline can be treated as one anticlinorium. Other large folds in the island are tentatively shown on Figure 8. Little can be said at this time about the relationships between these folds. The Mayagüez area seems to be mainly affected by the Maestrichtian deformation, whereas folding in other areas involves Paleocene and Eocene rocks.

Until recent years, most authors have ac-

cepted a late Cretaceous age for the major orogeny in Puerto Rico (Meyerhoff, 1933). A few (Hodge, 1920; R. C. Mitchell, 1954) consider the deformation as continuing from late

breccias south of San Juan, which he considers as uppermost Cretaceous or lowermost Paleocene, are petrographically similar to rocks "... in the hills on the north side of the Laja

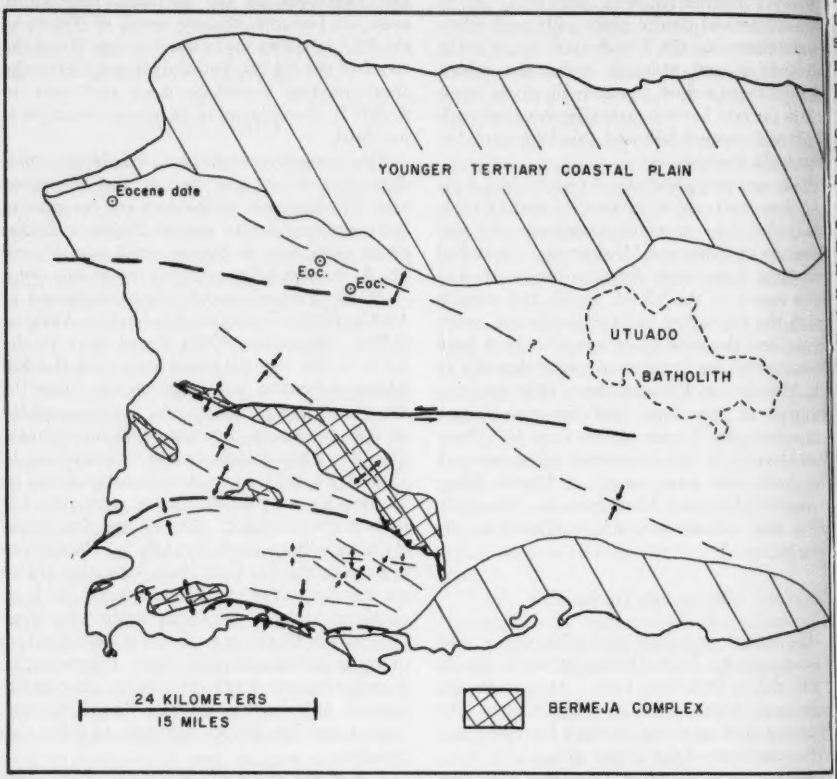

FIGURE 8.—GENERALIZED STRUCTURE OF WESTERN PUERTO RICO

Heavy lines show faults; light lines show fold axes; thrust-fault symbol points in the direction of dip of the fault.

Cretaceous into the Eocene. Kaye (1956, p. 120) considers that "... the principal orogeny which deformed the Puerto Rican older complex is early Tertiary and probably Eocene in age." Evidence in the Mayagüez and the Yauco areas shows that, while the Eocene orogeny (post-upper Paleocene, pre-middle Oligocene) is important, intensive folding also occurred in the Maestrichtian. Perhaps Kaye's Cretaceous exposures in northeastern and north-central Puerto Rico represent San Germán time and consist of rocks deposited after the Maestrichtian folding which were folded with the Paleocene and ?Eocene rocks. Kaye (1956, p. 120) mentions that hornblende andesite

Valley..." These rocks are the San Germán volcanic rocks.

Post-Cretaceous older complex rocks are found in northwestern and southwestern Puerto Rico, in southeastern Puerto Rico (E. A. Pessagno, Jr., personal communication), and in north-central and northeastern Puerto Rico (Kaye, 1956). With the completion of mapping in these areas, where older Tertiary rocks are more common than in southwestern Puerto Rico, the relative intensity of these deformations should become evident.

The following tentative generalizations can be made:

Large bodies of serpentinite are among the

oldest rocks in Puerto Rico; they may be either intrusive into or older than the pre-?Cenomanian sedimentary and volcanic rocks.

Southwestern Puerto Rico has been at or near sea level probably since Cenomanian time, covered by a relatively thin sedimentary sequence, whereas the rest of the island has received thick sedimentary and volcanic deposits.

Deformations in western Puerto Rico occurred in the: (1) pre-?Cenomanian; (2) Maestrichtian; (3) late Eocene-early Oligocene; and (4) post-middle Miocene.

The majority of rocks in Puerto Rico were deposited between the first and fourth deformations. The rocks formed between the first and third deformations, the older bedded sequence, are a complex mixture of extrusive volcanic rocks and shallow-water sedimentary rocks. The younger bedded sequence, Oligocene and Miocene rocks, includes shales, conglomerates, and limestones, none of which contain primary volcanic material.

The island as a whole was folded in pre-middle Oligocene time into broad open folds, in some places either overturned or asymmetric.

The deforming force was oriented north-northeast. In southwestern Puerto Rico the force seems to have been directed from the north-northeast, although the intensity of deformation, perhaps because of the thinning sedimentary cover, increases to the south.

Other islands in the Greater Antilles are formed of similar lithologies deformed in similar ways. In eastern Cuba Thayer and Guild (1947) find three types of serpentinite occurrences which are, from north to south: (1) thrust slices of serpentinite in Eocene and older rocks; (2) "...a number of east-west folds... (with) the serpentinite... exposed principally along the crests of three main anticlines" (p. 926); and (3) large domes of serpentinite unconformably below younger rocks in which "...although they formed topographic highs during much of late Cretaceous and Tertiary time, and must have been deeply eroded, no evidence of their floors has been found" (p. 929). The tectonic setting of the Mayagüez area is similar to the central zone of serpentinite anticlinal cores.

Hess and Maxwell have suggested a crustal downbuckle (1953) as the mechanism for the Antillean deformations. Because earlier workers in Puerto Rico considered that overturning on the island was to the north, large strike-slip faults were postulated to move Puerto Rico into a position north of a tectonic axis. Overturning in the Mayagüez area, with few exceptions, is to the south; further mapping must determine if this trend holds for the rest of the island. Southward overturning would imply a tectonic axis north of the island.

Another significant hypothesis is that serpentinite may represent the basement beneath the deformed sediments as well as intrusions near the tectonic axis. In parts of the world where only a thin continental-type crust overlies the mantle, perhaps exposures of serpentinite basement may actually be exposures of the mantle. Serpentinite belts in folded mountain chains may mark geanticiines flanking the tectonic axis; thus the trend of the serpentinite exposures is not necessarily related to emplacement of the serpentinite, but may be due to a later deformation.

Recently Thayer (1958) has discussed a third type of serpentinite intrusion, which he has found in Cuba and in eastern Oregon. It is a cold or "diapiric" intrusion often accompanying faulting in a terrain containing serpentinite, corresponding to the first type of serpentinite occurrence mentioned. Small exposures of this type of intrusion occur in the Mayagüez group in the Yauco area. On Route 118 southeast of San Germán a 2-m sliver of highly sheared serpentinite diapirically intrudes quartz diorite porphyry of post-Maestrichtian age. In this exposure a porphyry dike cuts serpentinite. Independent evidence mentioned elsewhere in this paper shows that the porphyry is much younger than the serpentinite, indicating that the former intrusive relationship does not give a valid age sequence.

Chubb (1955a; 1955b; unpub. paper presented at 1st Caribbean Geological Conference, Antigua, B.W.I., December, 1955) has pointed out that the rudists in parts of the Caribbean can be divided into faunal groups. He has described the *Barrettia* fauna characterized by the genus *Barrettia* and another fauna containing the genus *Titanosarcolites*. The two faunas can be separated in Jamaica and Cuba and probably in Mexico (Chipas) and in the Virgin Islands (St. Croix). He dates the *Titanosarcolites* fauna as early or middle Maestrichtian from evidence in Jamaica and Cuba. The *Barrettia* fauna is dated as most probably late Turonian-Coniacian (Chubb, unpub. paper, p. 10).

Chubb (Personal communication) has identified three rudist specimens (PR2099, PR2541, PR2905) as "*Barrettia*, near *B. monilifera*." PR2099 is from 1.5 km south of El Brujo, PR2541 from west of Parguera, PR2905 from

the southern Sierra Melones. The last two, from the Paraguera limestone, are dated Campanian by determinations from Foraminifera; nearby the first (from a slide-block exposure of the Mayagüez group) is probably Campanian. Possible reworked specimens are described in the section on paleontology of the San Germán formation. *Icthyosarcolites sp.* has been found north of Yauco (T. R. Slodowski, 1956, unpub. Ph.D. thesis, Princeton Univ., p. 77). It is named in the *Barrettia* fauna in Jamaica and in the *Tepeyacia* fauna in Cuba (Thiadens, 1936).

In the Mayagüez area rudists from the *Titanosarcolites* fauna are limited to limestone of the Maestrichtian Melones formation.

Heretofore, the range of the *Barrettia* fauna has been based mainly on the Jamaican succession, where the Coniacian to Campanian rocks are largely unfossiliferous clastic deposits. Elsewhere the range of *Barrettia* may be longer, as seems to be the case in Puerto Rico, where it extends into the Campanian.

Economic Geology

Detailed reports on mineral resources of southwestern Puerto Rico, especially the lateritic soils of Las Mesas, have been published by Fettke and Hubbard (1918), G. J. Mitchell (1922), Meyerhoff (1933), R. C. Mitchell (1954), and by the Puerto Rico Bureau of Mines (1941).

Small barite, barite-epidote, and barite-carbonate veins are common in the San Germán volcanic rocks near Route 314 and in the silicified rocks in the Sierra Bermeja, and an analysis of amphibolite from the eastern Sierra Melones (Table 1) shows a high barium content.

On the Tea road (Route 118) and extending eastward into Barrio Minillas, in an area of diorite and dacite dikes and sills, there are silicified and silicated medium- to thick-bedded limestones containing garnet (grossularite), epidote, and pyrite. In this vicinity the Puerto Rico Bureau of Mines (1941) also reports bornite "with appreciable silver values," gold in quartz veins, chalcopyrite, azurite, malachite, and galena.

Large areas of silicified porphyries contain hematite-magnetite, chlorite, and calcite replacing amphibole and feldspar phenocrysts, and silica and kaolinite replacing the matrix. The more intensely bleached specimens seem to have less chlorite and little calcite, and pyrite is common. The Puerto Rico Bureau of Mines (1941, p. 26, 41–42) lists small deposits of barite, manganese, and gypsum from west of Lajas, probably in one of the altered areas. A random sample (PR408) of the silicified porphyry showed 0.1 per cent copper; more testing and exploration for copper is justified in this area. The alterations seem to be due to hydrothermal action, commonly localized along faults but also found in large subcircular areas.

Dolomitic clays are developed on both sides of the western end of the Valle de Lajas, on limestone, serpentinite, and perhaps also on volcanic rock.

Road metal quarries are shown on Plate 1.

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